The role of buildings in U.S. energy system decarbonization by mid-century

Jared Langevin[1], Aven Satre-Meloy[1], Andrew Satchwell[1], Julia Olszewski[2], Kate Peters[2], Ryan Hledik[2] and Handi Chandra-Putra[1]

1 Lawrence Berkeley National Laboratory

2 The Brattle Group

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Executive summary

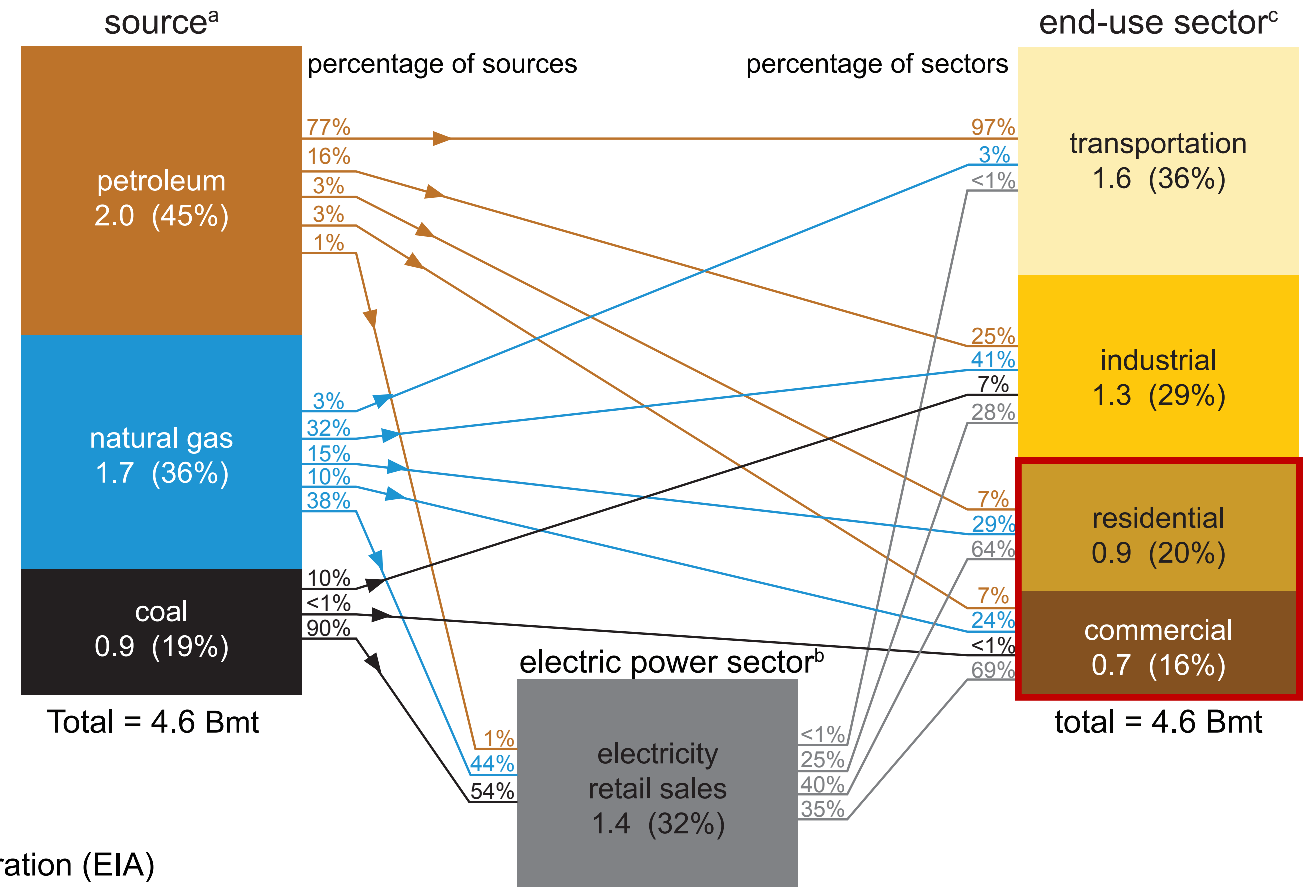
- We model three futures for U.S. building sector decarbonization to 2050
- Scenarios vary by levels of building efficiency, electrification and grid decarbonization
- Total building CO_2 emissions could be reduced up to ~90% vs. 2005 levels by 2050
- Nearly half of reductions are attributable to building efficiency and electrification measures, with the rest from further decarbonization of the building electricity supply
- Efficiency – particularly via envelope, HVAC, and water heating measures – is critical to achieving emissions reductions (as important as electrification)
- Aggressive electrification reduces emissions even under slow grid decarbonization
- The portfolio of building measures could provide annual power system cost savings of up to ~$100 billion per year by 2050 (before accounting for the cost of the measures)
- These power system cost savings represent ~30-40% of the incremental cost of decarbonizing the power supply
- ~70% of the portfolio's energy savings are cost-effective w/ our modeling assumptions

Part 1: An overview of our motivation, modeling approach and high-level building CO_2 emissions reduction potentials

Residential and commercial buildings are a top source of CO_2 and must be a key element of economy-wide decarbonization

U.S. CO_2 emissions from energy consumption by source and sector, 2020

billion metric tons (Bmt) of carbon dioxide (CO_2)



Source: U.S. Energy Information Administration (EIA)

We represent a comprehensive mix of residential and commercial decarbonization measures spanning most end uses

MEASURE* FEATURES

Beneficial Electrification (EL)
- Convert fossil heating, water heating, and cooking to electric service

Energy Efficiency (EE)
- Applies to electric and remaining non-electric loads
- Includes envelope efficiency/controls

Demand Flexibility (DF)
- Controls enable load shed/shift based on net system load conditions
- Integrate w/ electric EE/EL measures

COMPETING MEASURE TIERS

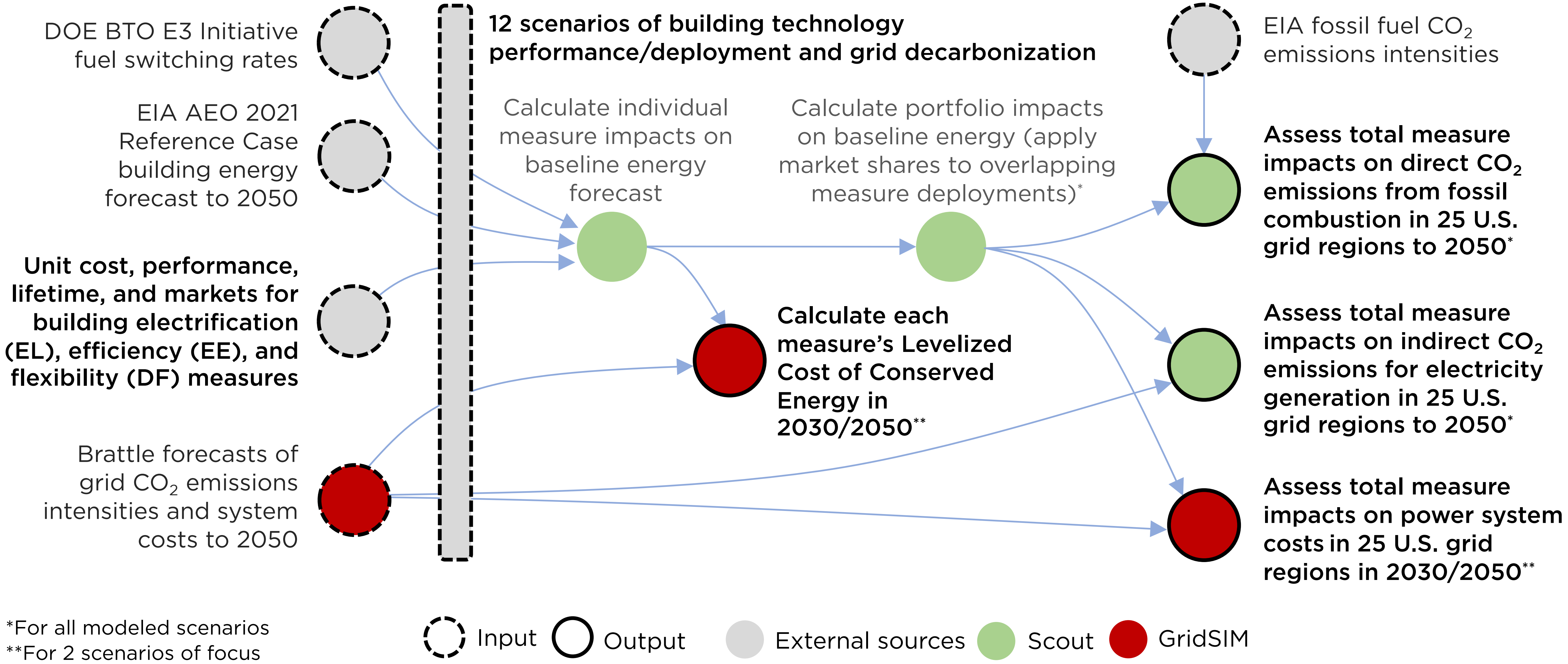
ESTAR/IECC/ASHRAE 90.1
- Consistent w/ latest guideline version, escalated over time; generally lower cost
- Basis for aggressive codes/stds. ”floor”

Best Available
- Consistent w/ best currently market-available, escalated over time; high cost
- Package EE and DF features

Prospective
- Consistent w/ BTO roadmaps and enter market later (2030/2035); ~5 yr. payback
- Basis for breakthrough tech. “ceiling”

*We assess 170 building measures and 37 measure packages, definitions available here

Building and grid decarbonization scenarios are simulated by integrating Scout and GridSIM model data, respectively

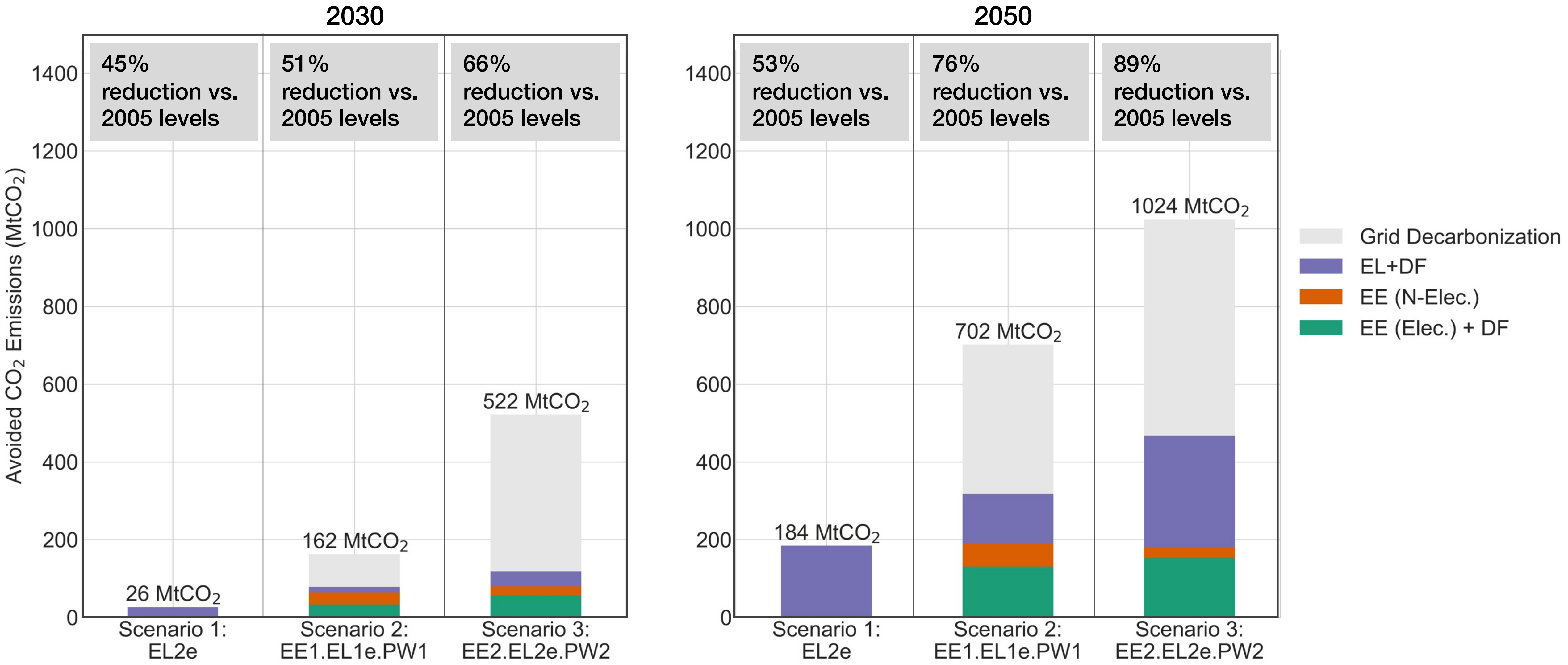


*For all modeled scenarios
**For 2 scenarios of focus

Three benchmark scenarios are differentiated primarily by levels of efficiency, electrification, and grid decarbonization

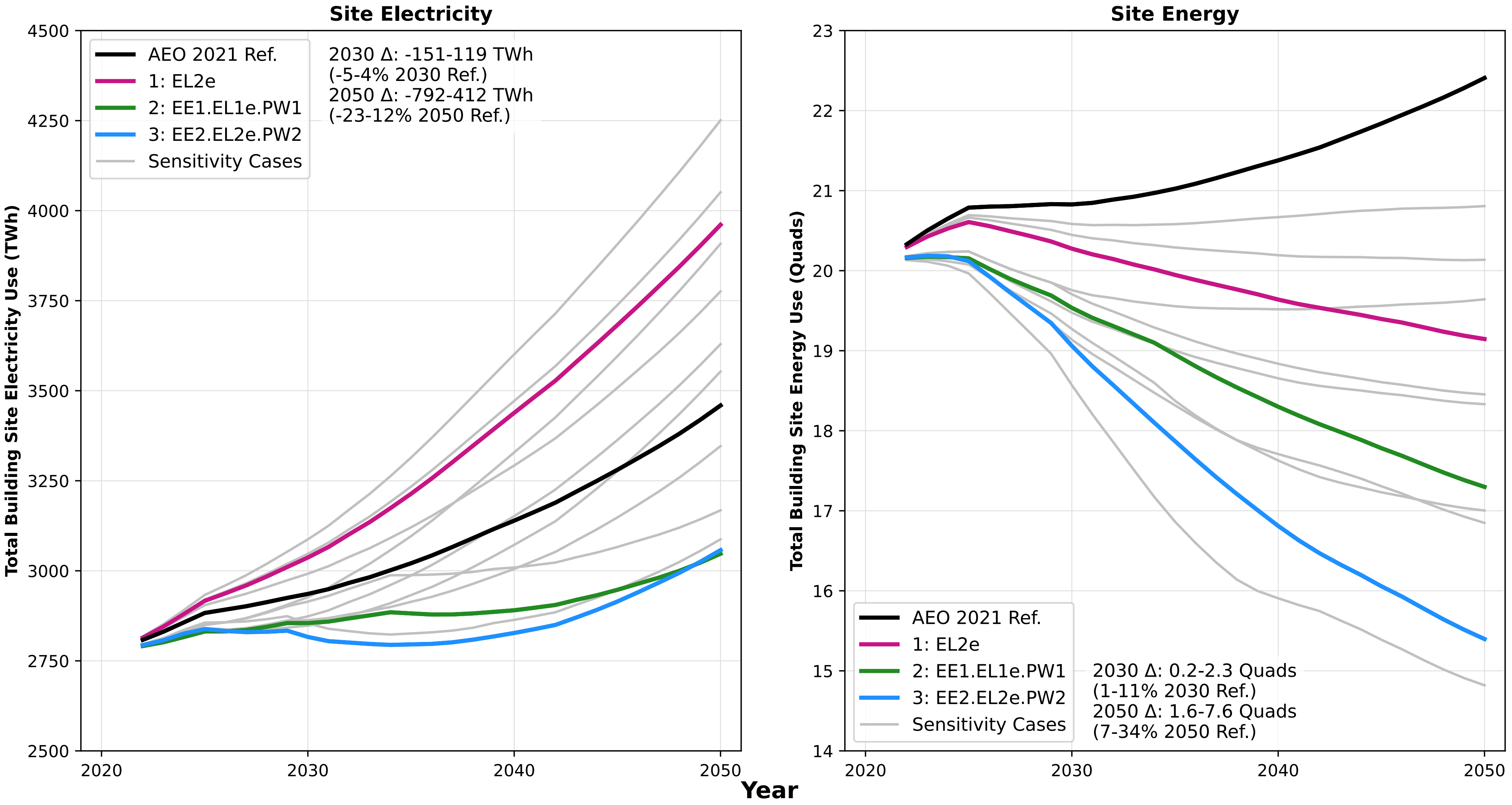
Benchmark scenario	Efficiency and electrification	Grid decarbonization	Question addressed
1: Lower bound (EL2e)	Aggressive Electrification Only	Reference Case (AEO 2021)	What is the impact of aggressive electrification on emissions without efficiency and under slow grid decarbonization?
2: Middle ground (EE1.EL1e.PW1)	Moderately Aggressive	Moderately Aggressive (80x2050)	Is mostly market-driven demand-side measure deployment with moderate grid decarbonization sufficient to yield deep reductions in building emissions?
3: Upper bound (EE2.EL2e.PW2)	Aggressive	Aggressive (100x2035)	How deeply can building emissions be reduced under a best-case scenario of demand-side measure deployment and grid decarbonization?

Building emissions are reduced 51-66% vs. 2005 levels by 2030 and 76-89% by 2050 under middle-upper benchmark scenarios



Part 2: The key policy-related dynamics and energy end uses driving building CO_2 emissions reductions

Several sensitivity cases are run alongside scenario benchmarks, resulting in a range of energy and CO_2 trajectories to 2050



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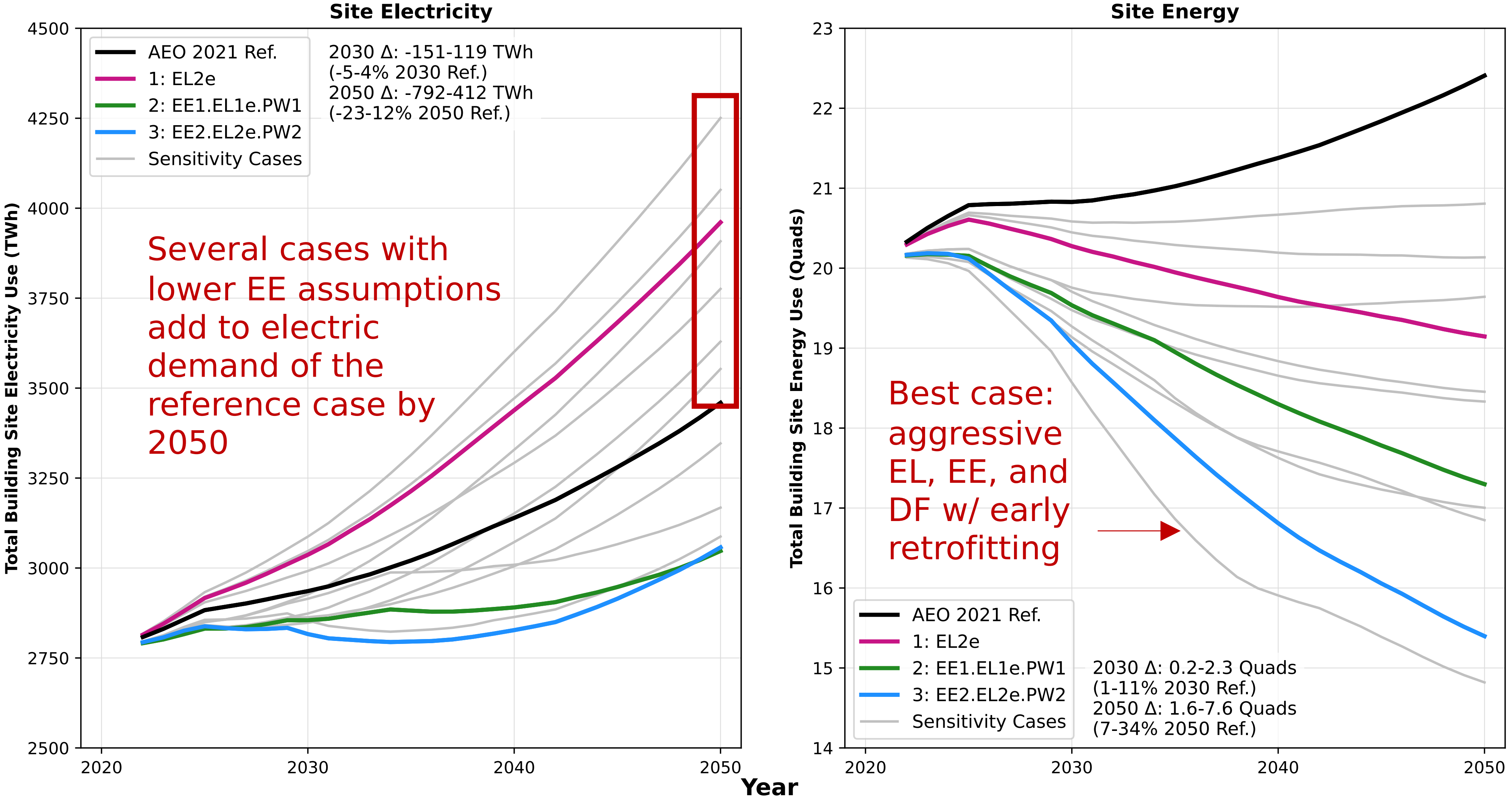

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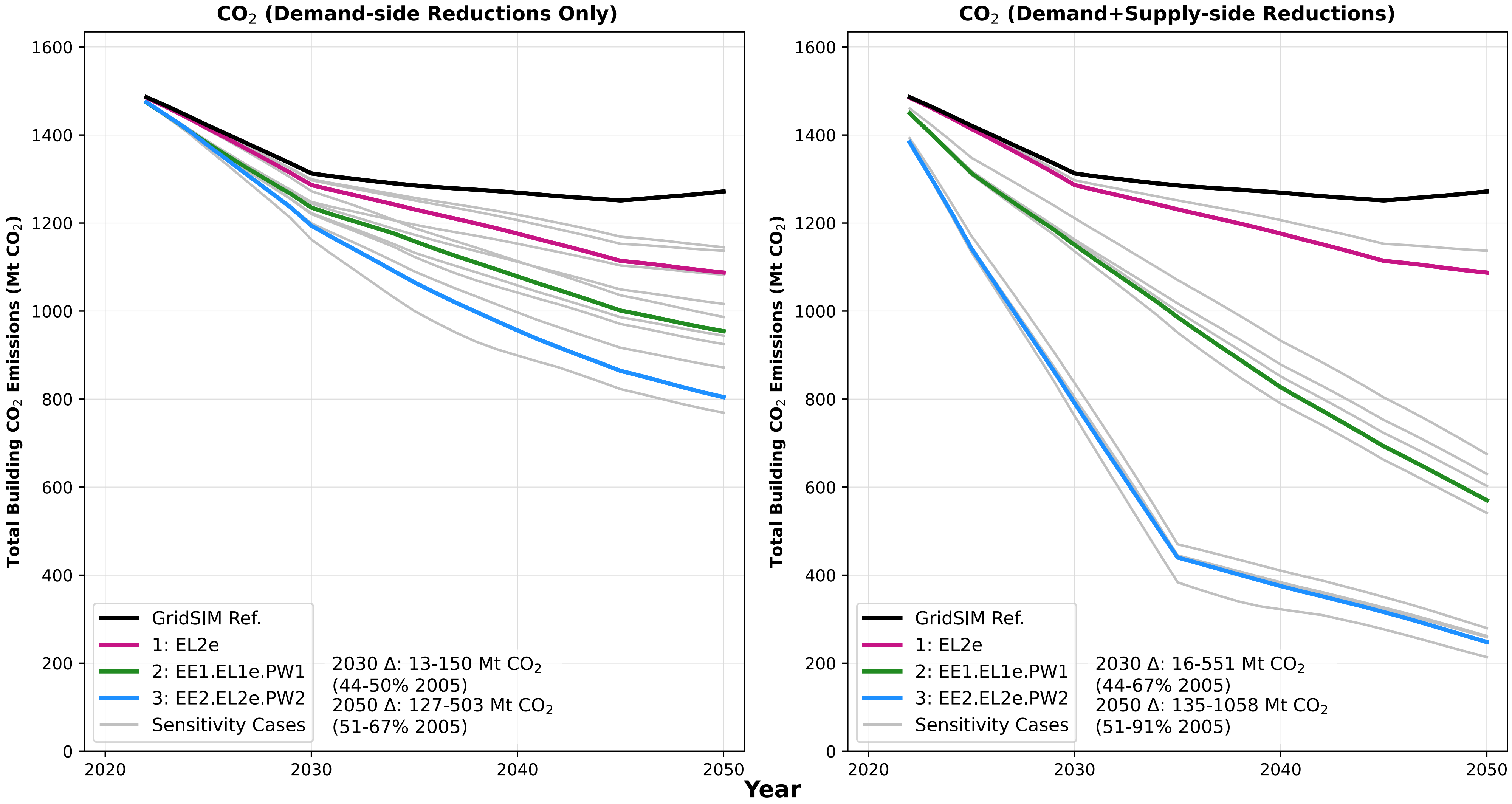

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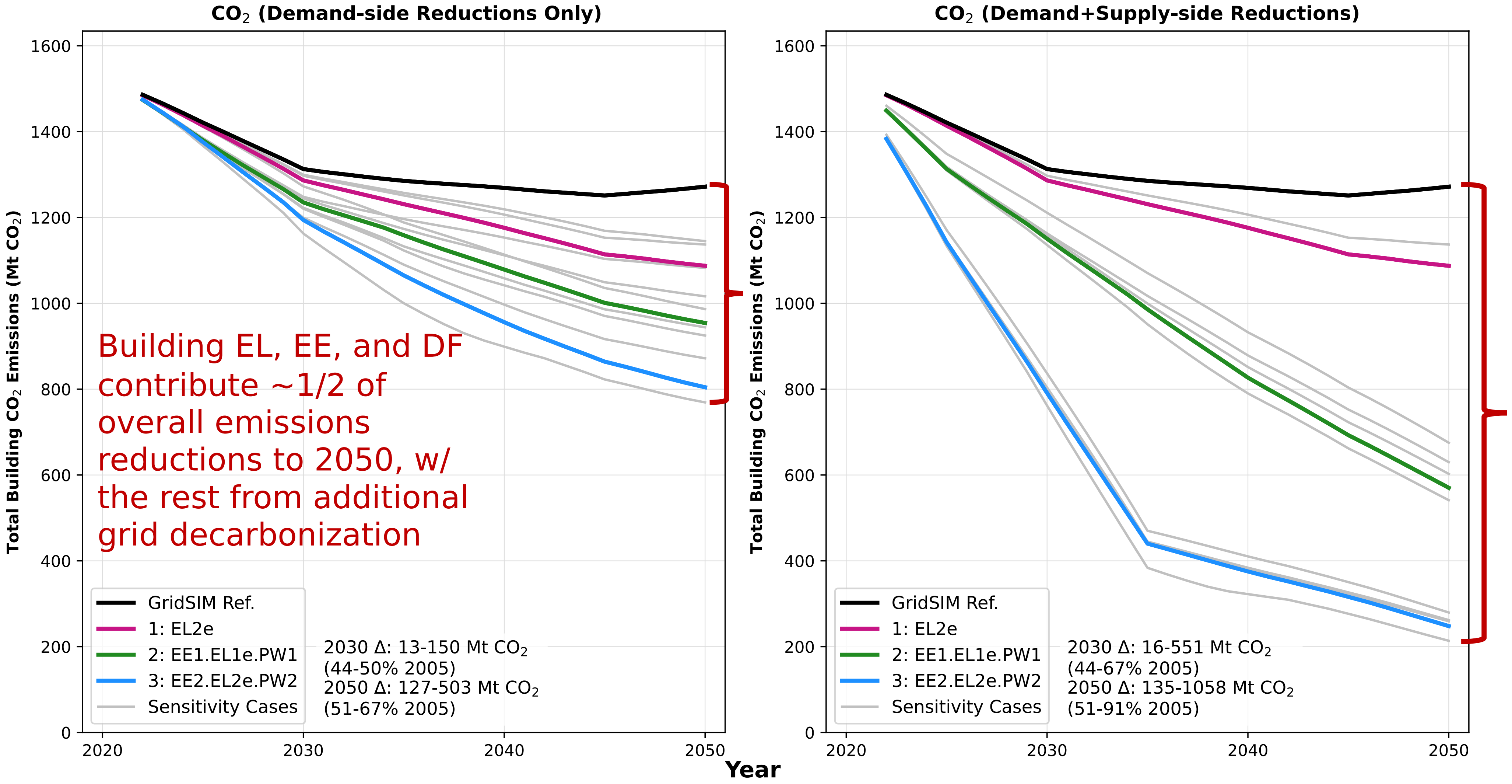
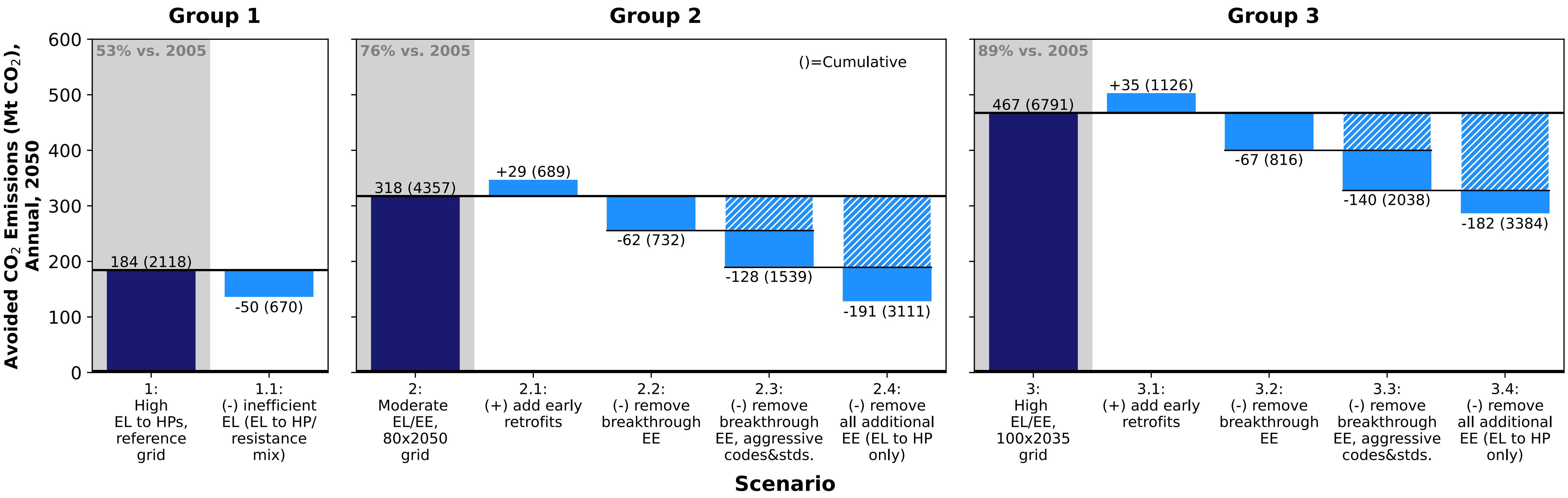


2050 demand-side CO_2 reductions: The absence of aggressive efficiency deployment substantially limits reductions



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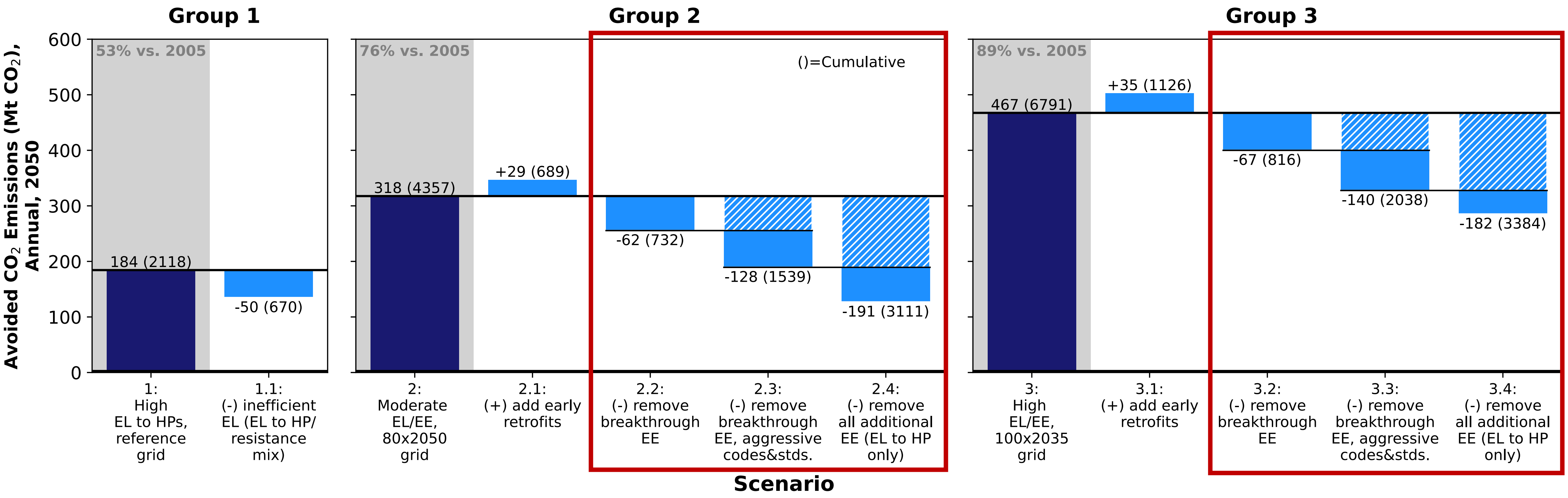

Successive removal of key EE dynamics has incrementally large and negative effects that are robust to different grid conditions

Thermal end uses drive reductions across scenarios; building measures drive ~45% of savings in Scn. 2–3

Benchmark scenario	Efficiency and electrification	Grid decarbonization
1: Lower bound (EL2e)	Aggressive Electrification Only	Reference Case (AEO 2021)
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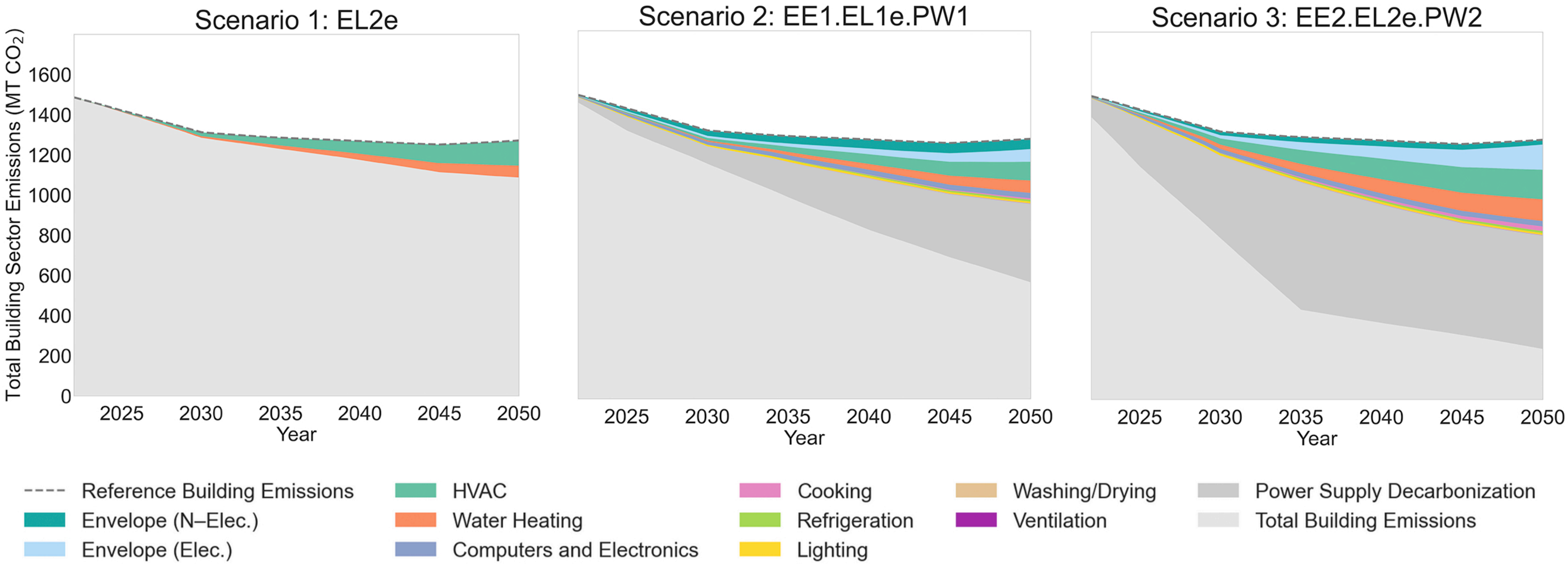

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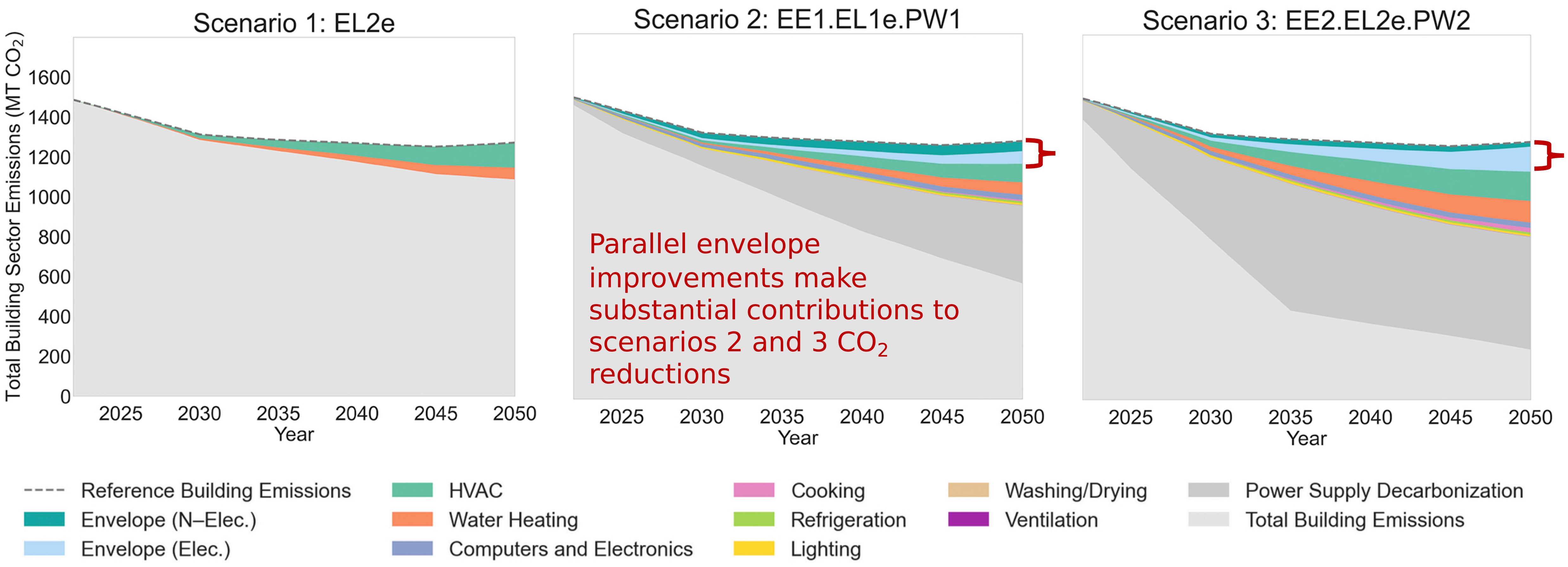

Part 3: A deeper look at the sources of building CO_2 emissions reductions under moderate decarbonization assumptions

Scenario 2 focus: Summary of assumptions for key building dynamics and power sector decarbonization

Market-Available Tech. Perf. Range		Load Electrification		Early Retrofits	Power Grid
Raise Floor	Raise Ceiling	Switching Rate	Efficiency Level		
Moderate (more aggressive codes and standards take effect in 2030)	Moderate (mkt. entry of breakthrough tech. in 2035)	Moderate (E3 Optimistic)	Switch to HPs	None	Moderate (GridSIM 80x2050)

Scn. 2 CO_2 savings: EE measure reductions are nearly double those of EL (which grow over time)

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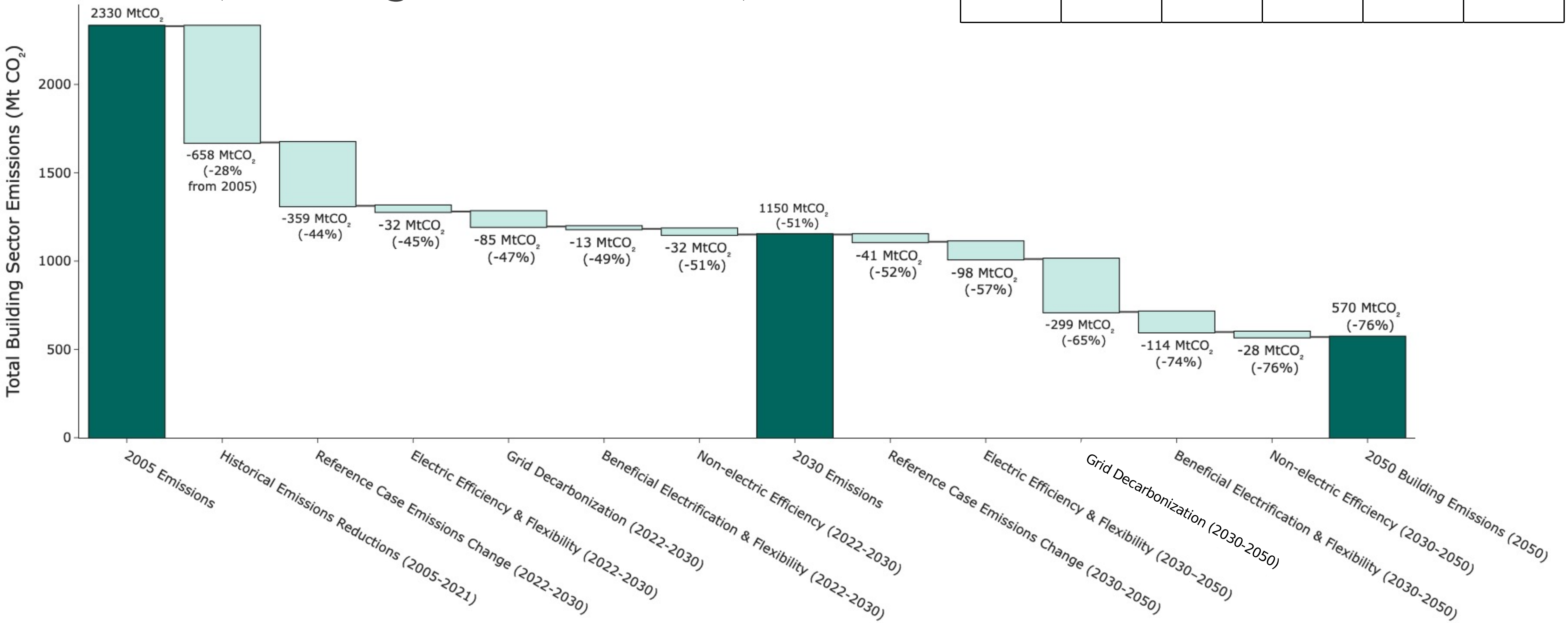

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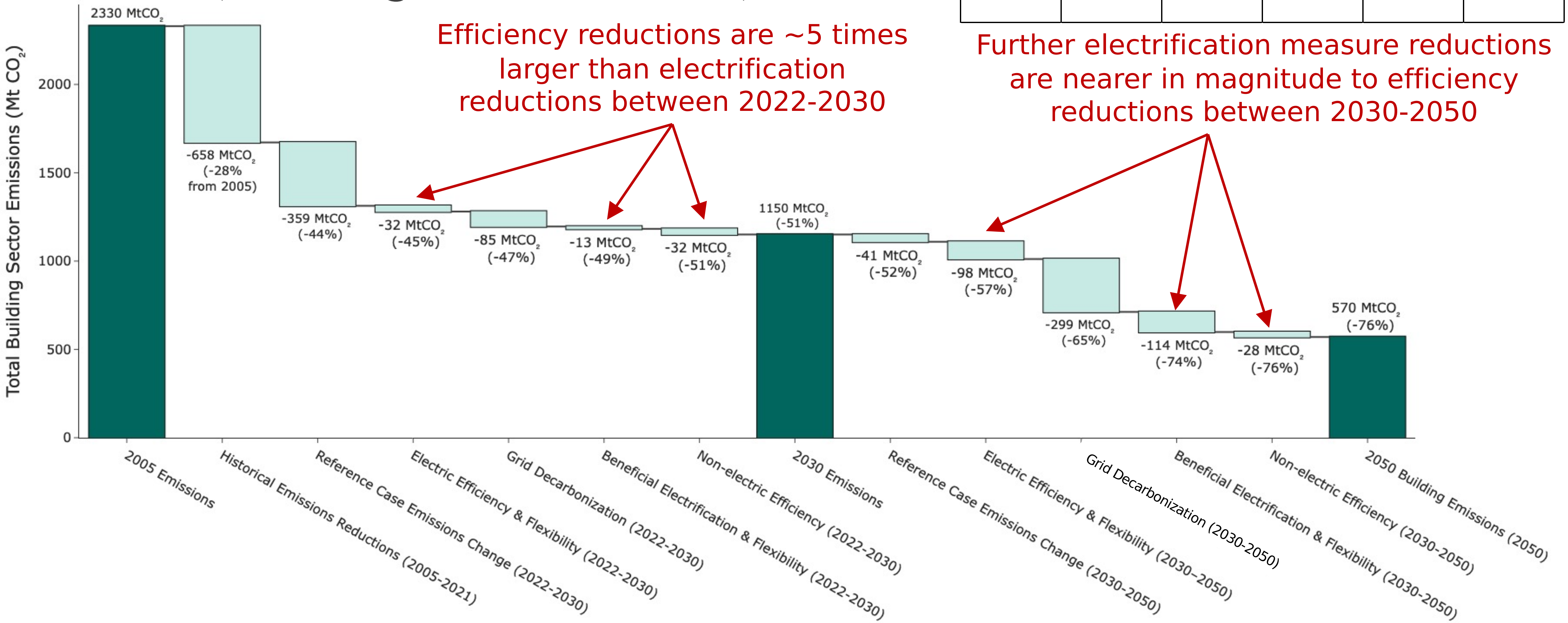
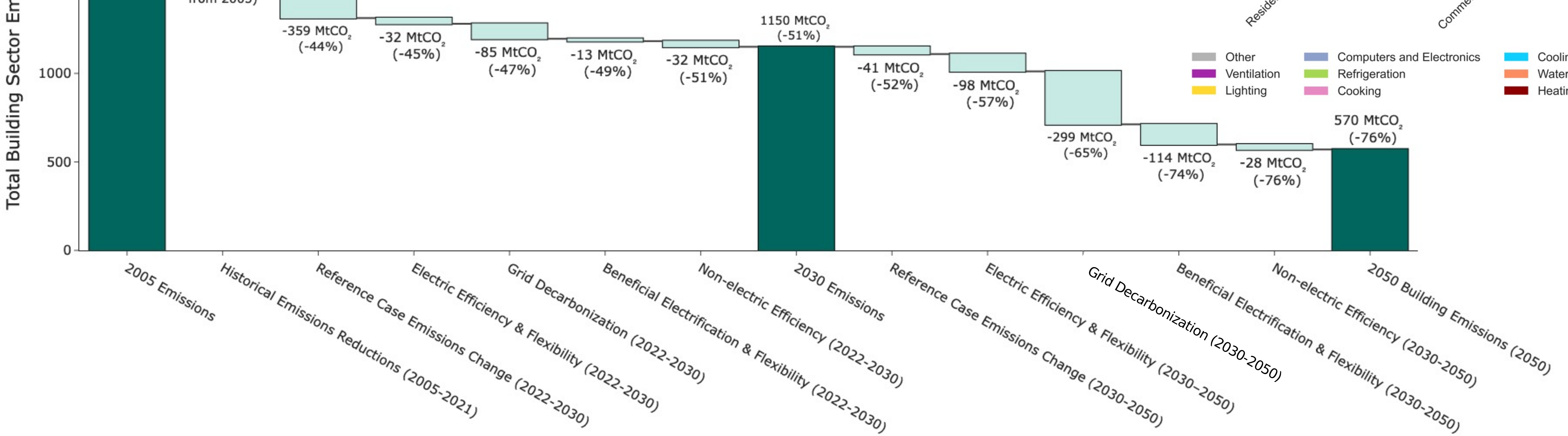
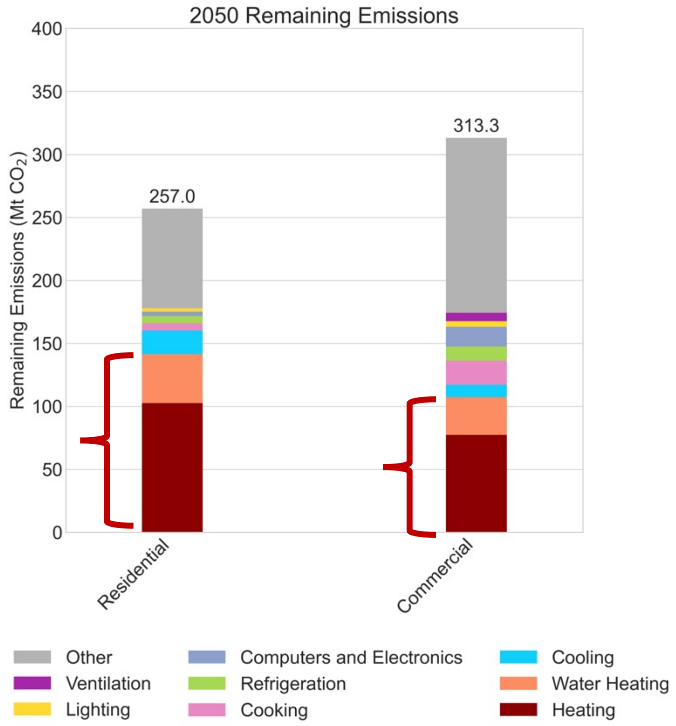


Scn. 2 CO_2 savings: EE measure reductions are nearly double those of EL (which grow over time)

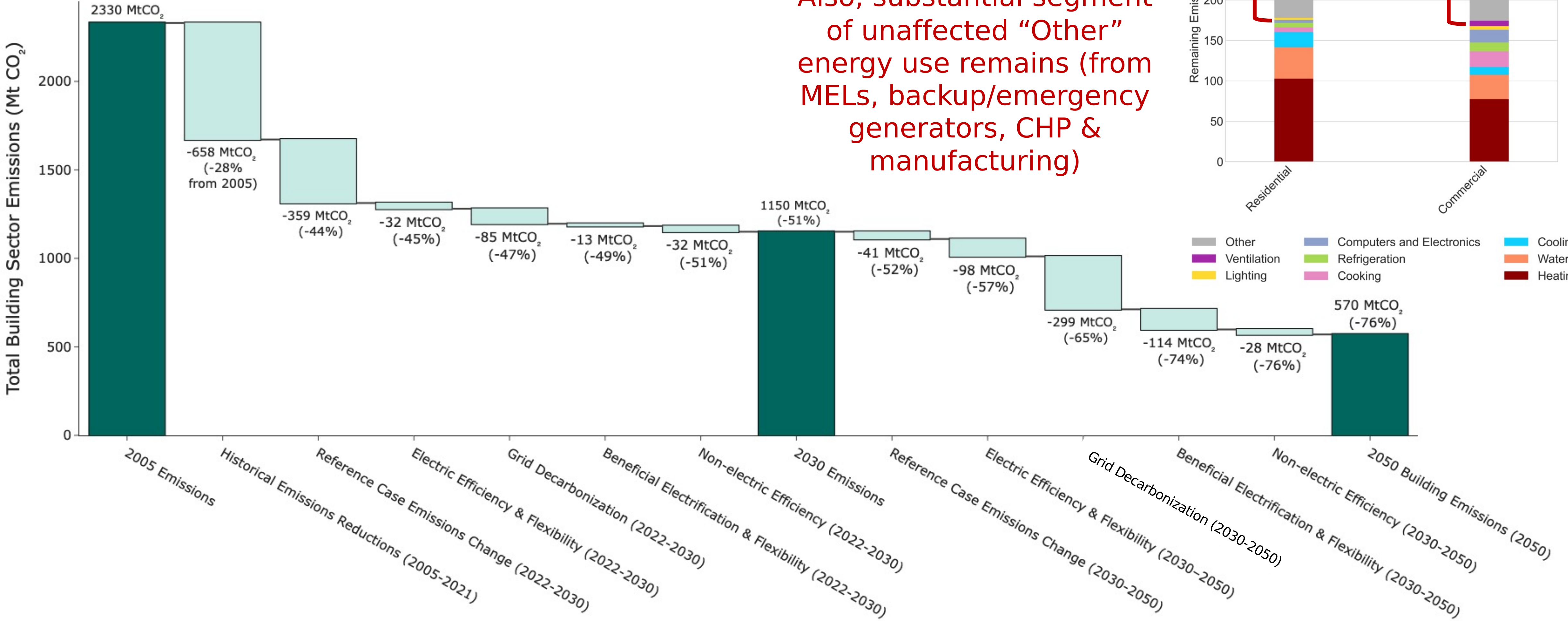
Remaining emissions are driven by residual thermal loads (space/water heating) that do not switch to electricity

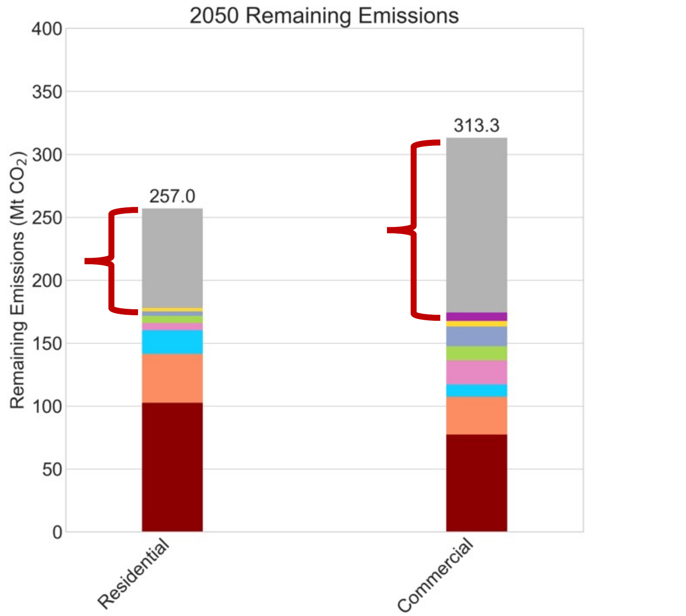




Scn. 2 CO_2 savings: EE measure reductions are nearly double those of EL (which grow over time)

Also, substantial segment of unaffected "Other" energy use remains (from MELs, backup/emergency generators, CHP & manufacturing)

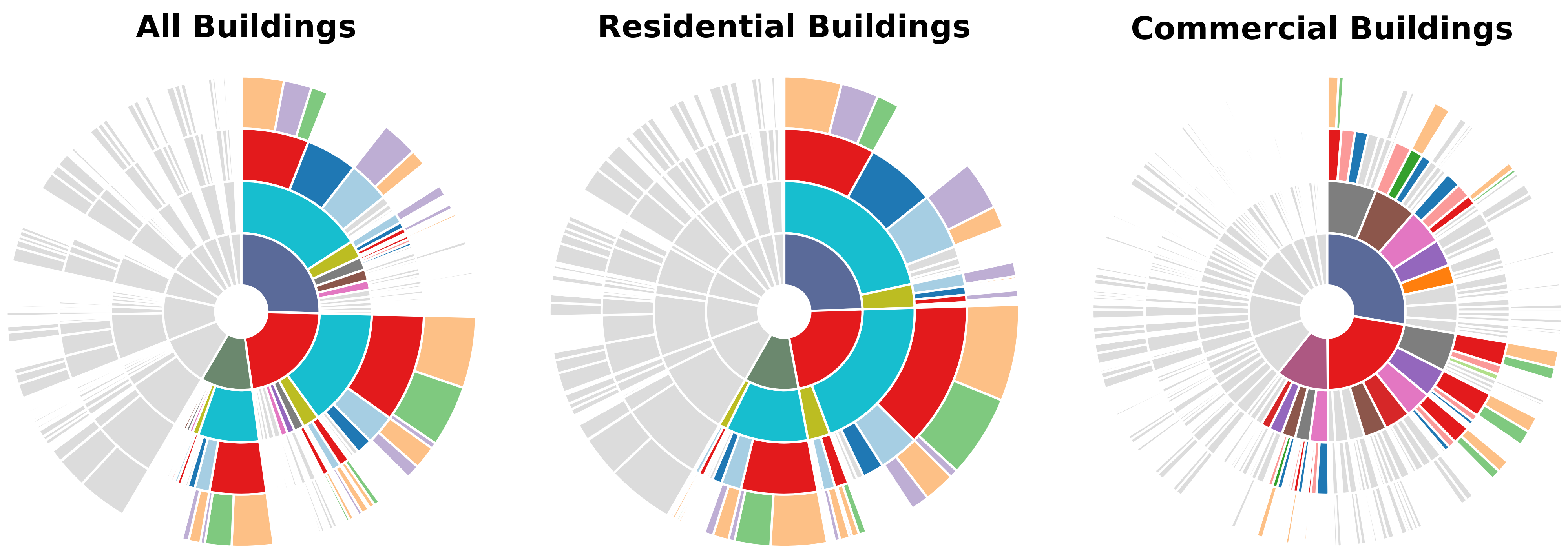




Scn. 2 2030 CO_2 reductions: Strongly driven by envelope EE improvements in single family homes with non-electric heating

*In this visualization, the top three regions are highlighted with color, as are the top segments for each nested level within those regions (e.g., building type, end use, measure type); all other segments are shaded gray

Scn. 2 2050 CO_2 reductions: More influence from EL/electric EE measures; single family homes continue to drive reductions



Regions (L1)	Building Types (L2)	End Uses (L3)	Measure Types (L4)
Lakes/Mid-Atl.	Single Family Homes	Heating	EL+DF
Southeast	Multi Family Homes	Water Heating	EE (Elec.)+DF
Northeast	Retail	Cooling	EE (N-Elec.)
Upper Midwest	Education	Cooking	
Texas	Hospitality	PCs/Electronics	
California	Assembly/Other	Refrigeration	
Lower Midwest	Large Offices	Other	
Northwest	Hospitals	Lighting	
Great Basin	Small/Medium Offices	Ventilation	
Rocky Mountains	Warehouses		
Southwest			

*In this visualization, the top three regions are highlighted with color, as are the top segments for each nested level within those regions (e.g., building type, end use, measure type); all other segments are shaded gray

Part 4: Implications of aggressive building electrification, efficiency, and flexibility for power system decarbonization

Introduction

Our prior research identified the critical role that energy efficiency (EE), demand flexibility (DF), and electrification (EL) can play in decarbonizing the power sector.

These demand-side initiatives also will reduce the cost of decarbonizing the power system. The role of EE, DF, and *efficient* EL in facilitating an affordable decarbonization transition is a similarly important consideration.

The purpose of this analysis is to estimate the extent to which demand-side initiatives can decrease the cost of decarbonizing the U.S. power system.

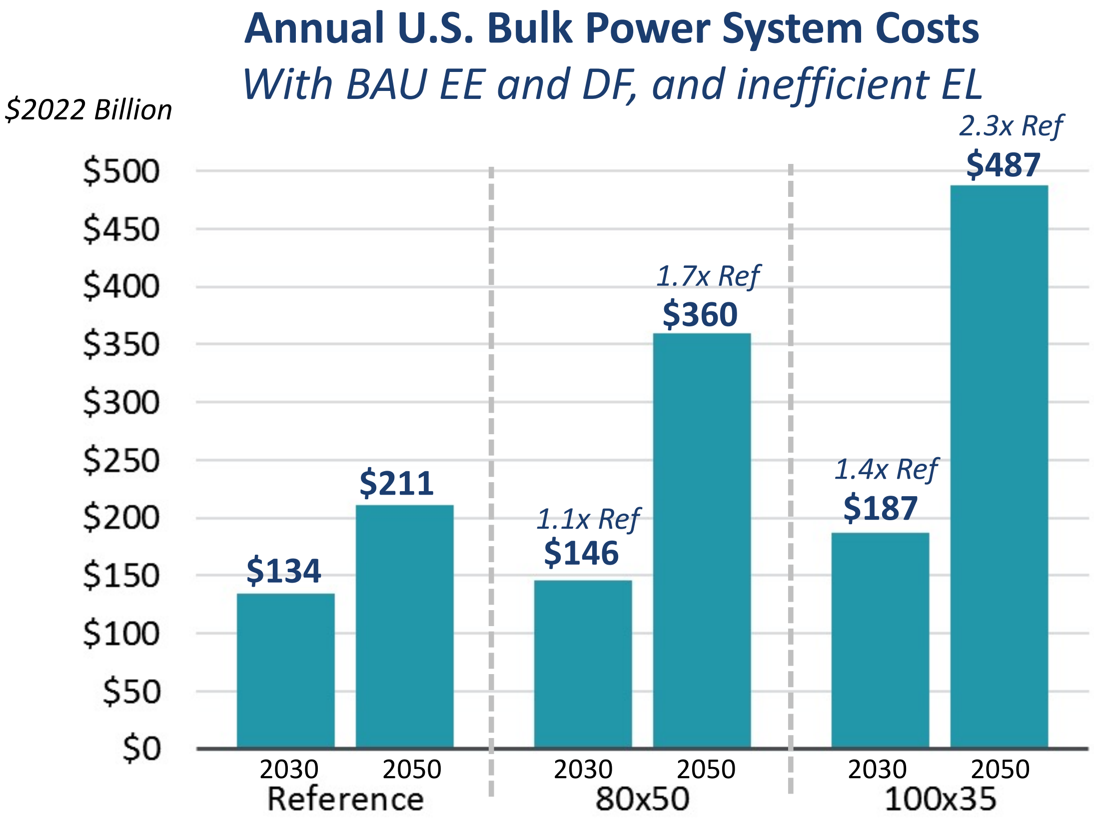
We analyze the same EE, DF, and EL measures presented previously to determine:

- Each individual measure's cost-effectiveness from a system-level perspective
- The cost savings (net of measure costs) associated with all cost-effective EE and DF measures in the portfolio, as well as efficient EL

PRELIMINARY DRAFT RESULTS

Power system costs with business-as-usual EE, DF, and inefficient EL

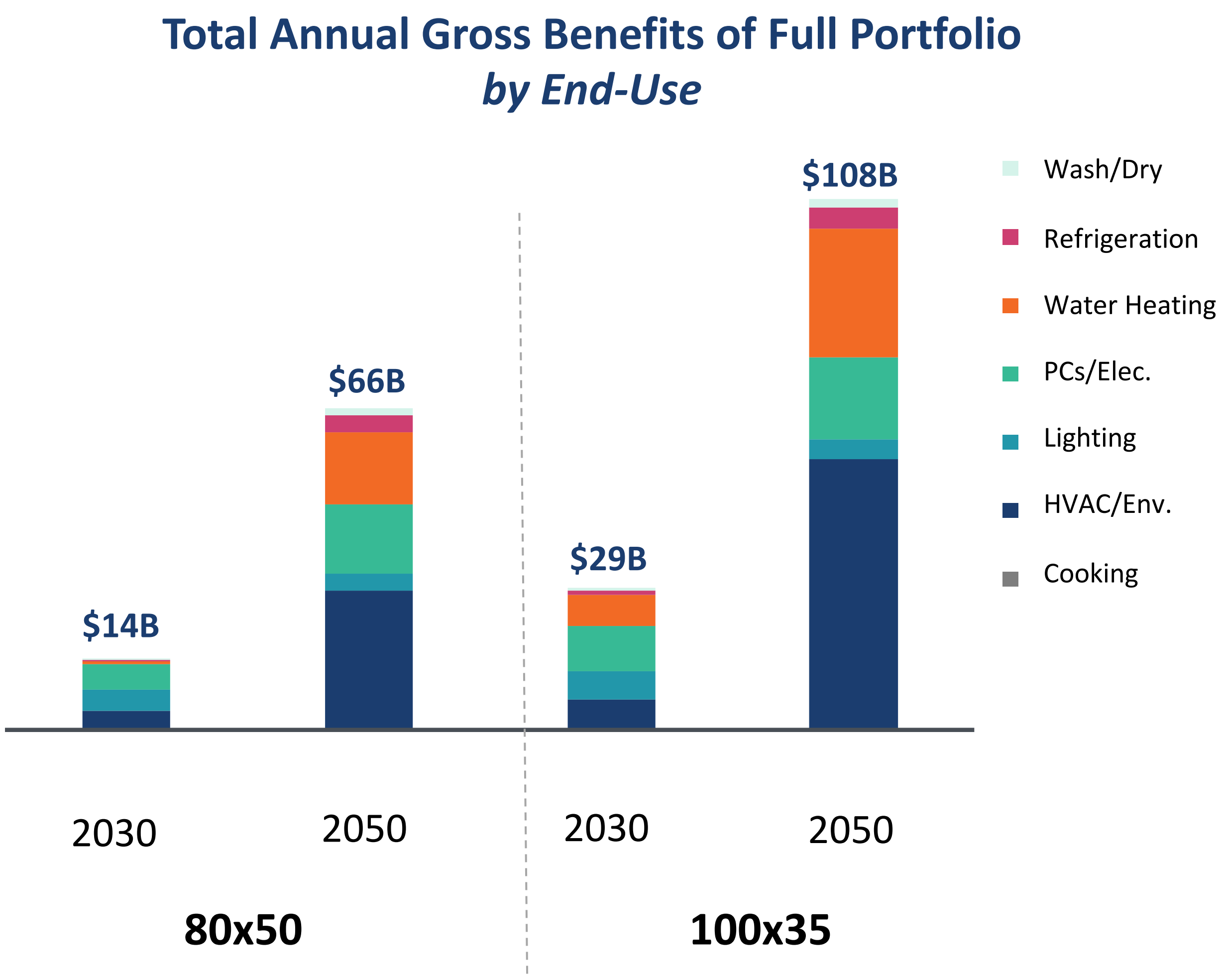
Decarbonizing the U.S. power sector without significant new demand-side initiatives could increase total annual system costs by more than 2x by 2050.

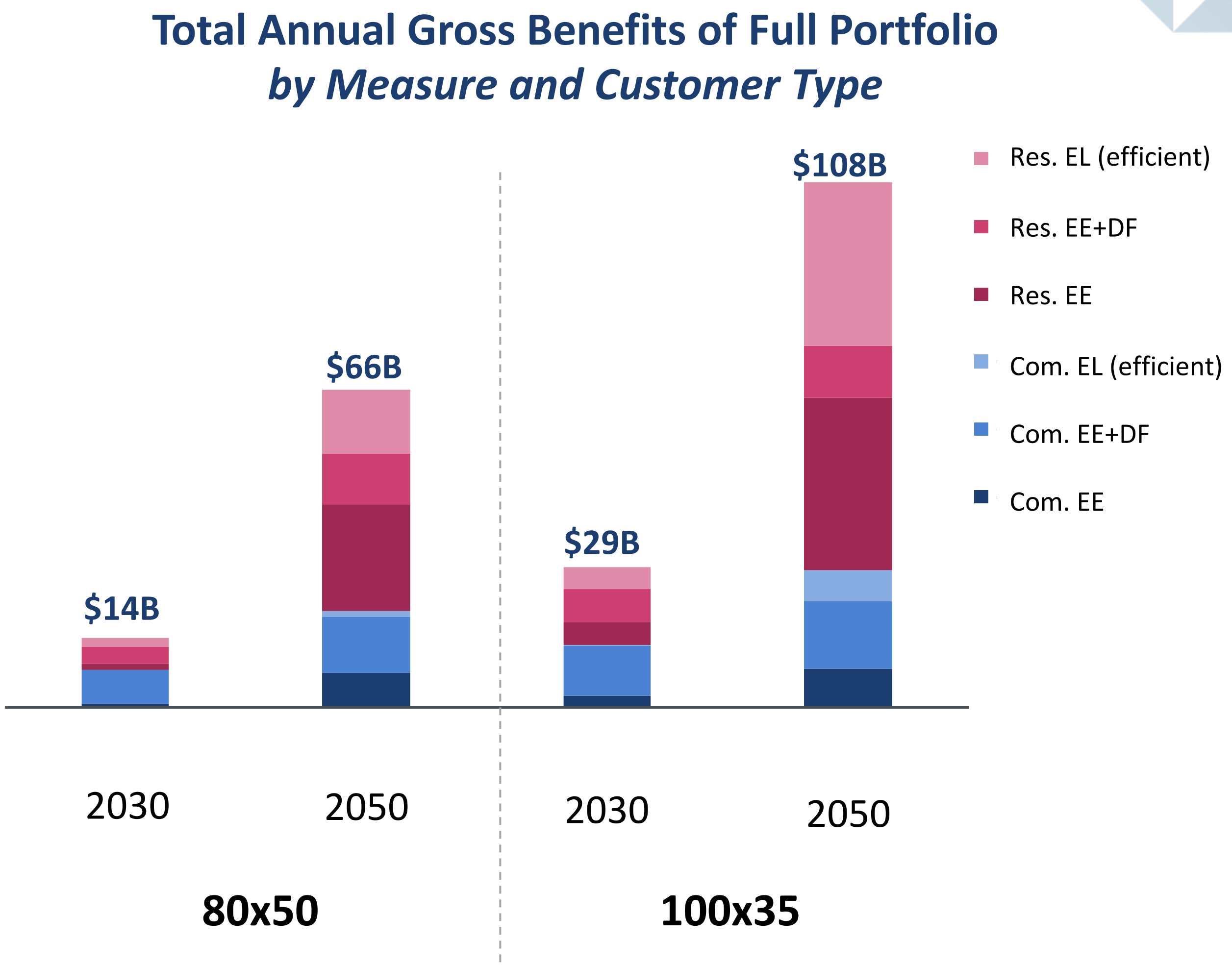


PRELIMINARY DRAFT RESULTS

Note: Costs shown are only power generation costs (capital expenditures and production costs) and exclude federal tax subsidy costs (ITC/PTC). Electricity delivery-related costs (transmission and distribution) and energy costs from other sectors are not included.

Gross benefits of the full portfolio





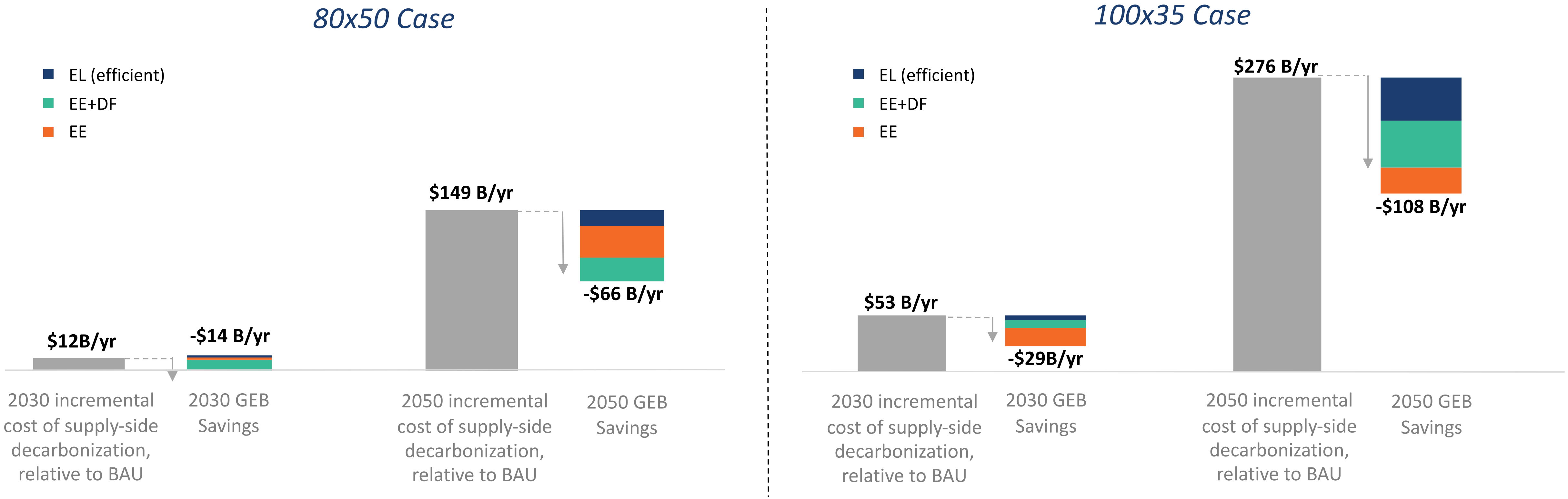
PRELIMINARY DRAFT RESULTS

Note: Gross benefits represent avoided energy system costs, derated for measure competition. Electrification (EL) measure benefits represent savings from switching from an inefficient to an efficient EL measure, yielding positive grid benefits in our analysis.

Gross benefits of the full portfolio

To put the cost savings in context, in 2050 gross benefits of the total portfolio would offset approximately 30-40% of the incremental cost of decarbonizing the power system.

Reduction in Incremental Cost of Power System Decarbonization due to EE, DF, and Efficient EL

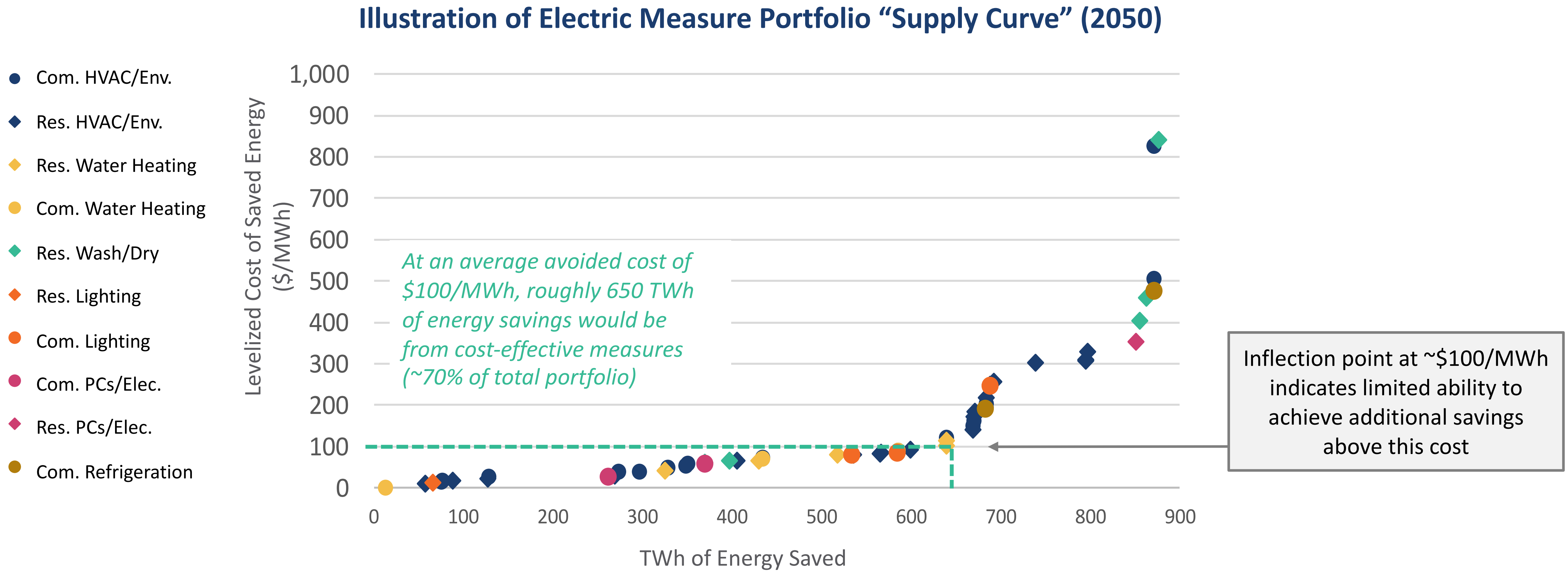


PRELIMINARY DRAFT RESULTS

Note: $2022. Measure savings are derated to account for measure competition. Electrification (EL) measure benefits represent savings from switching from an inefficient to an efficient EL measure, yielding positive grid benefits in our analysis.

Identifying cost-effective EE, DF, and EL measures

The cost-effective portfolio includes all measures for which benefits exceed costs.



PRELIMINARY DRAFT RESULTS

Note: Energy savings shown in chart account for competition among measures. The measure-level impacts are additive. 12 additional TWh saved are cut from the right-hand side of the figure because their LCOE exceeds $1,000/MWh.

Additional insights on fugitive emissions are forthcoming; the analysis is flexible to future updating

- **Scout simulations are now able to model the fugitive emissions impacts of energy efficiency and electrification, which will be added to scenario results in the future**
  - Methane leaks associated with natural gas service, refrigerant leaks associated with AC, heat pumps, and refrigeration
    - Represent deployment of low GWP refrigerant alternatives
- **The insights from our analysis do not end with these slide decks; we designed our analysis for active updating as needed to address new questions**
  - All code and measures are openly developed via the Scout GitHub repository
  - Benchmark scenarios will be included in the May update of the Scout Core Measures database, which has been updated annually since 2019
  - Measures are easily adapted to capture technologies of current interest to policymakers

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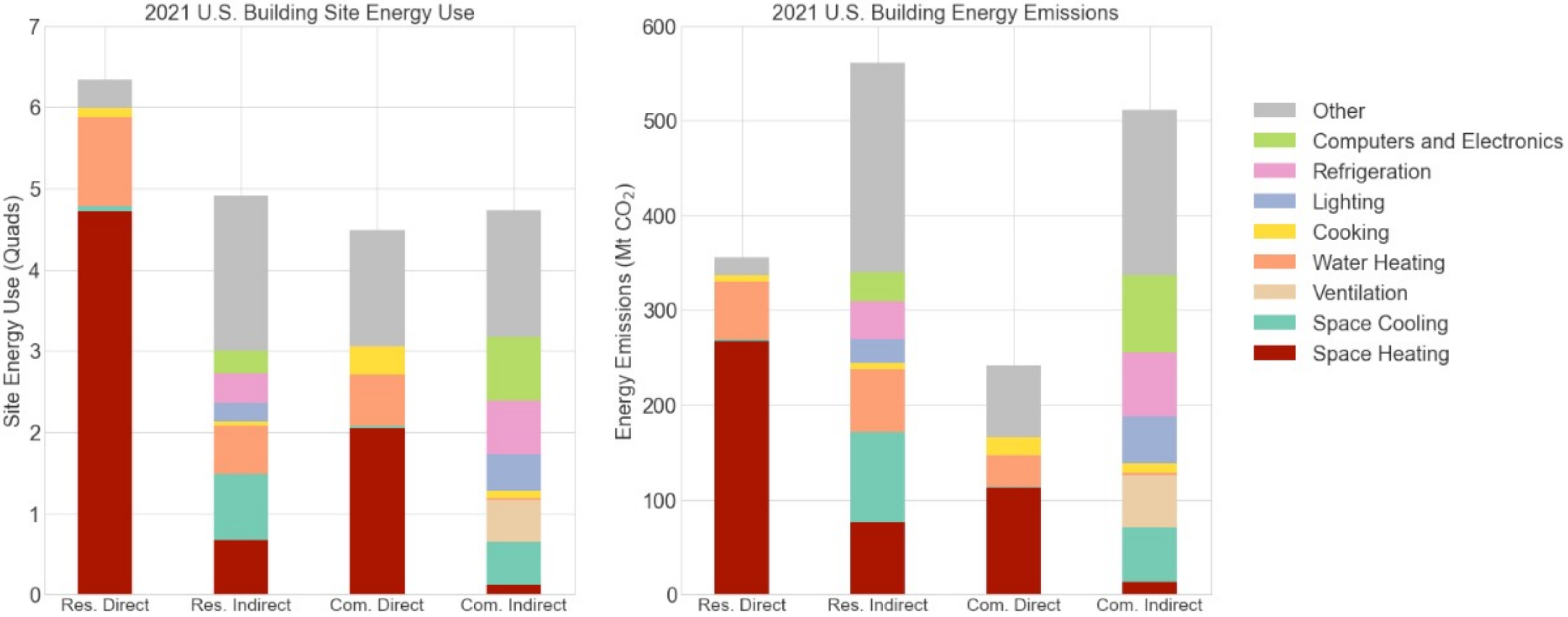
Thank you

A1: Additional context about the buildings sector and our overall modeling approach

Building energy CO_2 emissions are strongly driven by space conditioning and water heating – particularly in residences



Notes: Data are from DOE's Scout modeling tool. Residential "Other" includes miscellaneous electric loads, backup generators, pool heaters, and outdoor grills. Commercial "Other" includes emergency generators, CHP in commercial buildings, manufacturing, and other commercial building loads classified by EIA as "non-building loads".

Our analysis assesses the effects of measures and dynamics that can be mapped to BTO strategy pillars and programs

REFERENCE CASE

AEO 2021 Reference Case building demand

- Appliance standards already in Federal Register
- Code-driven shell improvements for new buildings
- Modest controls impacts (esp. lighting) in commercial buildings
- Generally slow improvement in market-available efficiency measures, except LEDs

BUILDING MEASURE* FEATURES

Beneficial Electrification (EL)

- Convert fossil-based heating and WH to heat pumps (and, in some scenarios, resistance)
- Convert fossil-based cooking to electric (no performance improvement)

Energy Efficiency (EE)

- Applies to electric/remaining non-elec. loads
- Persistent equipment performance improvements (particularly for electric)
- Couple with envelope efficiency, controls

Demand Flexibility (DF)

- Controls enable load shed/shift based on *net* system load conditions (load net renewables)
- Integrate with electric EE/EL measures

BUILDING DYNAMICS

Add near-term efficiency

- Market-competitive tech. (envelope/ctls.) that isn't represented in reference case

Elevate min. performance

- Raise market-available performance "floor"

Introduce breakthrough tech.

- Raise market-available performance "ceiling"

Accelerate electrification

- Escalate annual fuel switching rates

Accelerate retrofit decisions

- Add annual early replacement rates

* We assess 170 building measures and 37 measure packages, definitions available here

Demand-side (BTO Scout)

AEO 2021 Reference demand + GridSIM Ref. grid CO_2 factors

Supply-side (Brattle GridSIM)

GRID DECARBONIZATION

- Emissions decline to target by certain year

Scenario group 1: Aggressive building electrification without additional efficiency deployment, grid decarbonization stalls

Scenario	Narrative	Market-Available Technology Performance Range (EE)		Load Electrification (EL)		Early Retrofits (RT)	Power Grid (PW)
		Raise Floor	Raise Ceiling	Switching Rate	Efficiency Level		
1: EL2e ***Group 1 benchmark, High EL to HPs, reference grid***	Policy makers use both regulations and market-based instruments to dramatically accelerate electrification to heat pumps, but progress on electric grid decarbonization stalls, leaving the power sector far short of full decarbonization by mid-century.	BAU (AEO Reference Case)	BAU (AEO Reference Case)	Aggressive (E3 Most Aggressive)	Switch to HPs	None	BAU (GridSIM Reference Case)
1.1: EL2 *(-) inefficient EL (EL to HP/ resistance mix)*	Reduction in EL efficiency representated by less efficient electric resistance heating and water heating technologies and fewer efficient heat pumps replacing gas end-uses.				Switch to Resistance/ HPs		

Scenario group 2: Moderate deployment of efficiency and electrification while the grid decarbonizes 80% by 2050

Scenario	Narrative	Market-Available Technology Performance Range (EE)		Load Electrification (EL)		Early Retrofits (RT)	Power Grid (PW)
		Raise Floor	Raise Ceiling	Switching Rate	Efficiency Level		
2: EE1.EL1e.PW1 ***Group 2 benchmark, Moderate EL/EE, 80x2050 grid***	Policy makers rely mostly on market-based instruments to moderately increase deployment of efficient technology and electrification to heat pumps; the power sector continues to decarbonize rapidly, but some electricity emissions remain in 2050.	Moderate (more aggressive codes and standards take effect in 2030)	Moderate (mkt. entry of breakthrough tech. in 2035)	Moderate (E3 Optimistic)	Switch to HPs	None	Moderate (GridSIM 80x2050)
2.1: EE1.EL1e.RT.PW1 *(+) add annual early retrofits*	Early retrofit behavior - encouraged by incentives and targeted policy programs - accelerates the introduction of both efficient technologies and fuel switching from fossil-based to electric equipment.					Increased*	
2.2: EE1a.EL1e.PW1 *(-) remove breakthrough EE*	Building technologies with breakthrough performance/cost characteristics never achieve market viability.		BAU			None	
2.3: EE1b.EL1e.PW1 *(-) remove breakthrough EE, remove aggressive codes and standards*	Building technologies with breakthrough performance/cost characteristics never achieve market viability AND efficiency codes and standards that are more aggressive than those in the reference case are never implemented.	BAU					
2.4: EL1e.PW1 *(-) remove all additional EE (EL to HP only)*	No additional efficiency improvements beyond the reference case are achieved; only electrification to heat pumps is represented.						

Scenario group 2: Moderate deployment of efficiency and electrification while the grid decarbonizes 80% by 2050

<table>
<tr><th rowspan="2">Scenario</th><th rowspan="2">Narrative</th><th colspan="2">Market-Available Technology Performance Range (EE)</th><th colspan="2">Load Electrification (EL)</th><th rowspan="2">Early Retrofits (RT)</th><th rowspan="2">Power Grid (PW)</th></tr>
<tr><th>Raise Floor</th><th>Raise Ceiling</th><th>Switching Rate</th><th>Efficiency Level</th></tr>
<tr><td>3: EE2.EL2e.PW2
Group 3 benchmark, High EL/EE, 100x2035 grid</td><td>Policy makers use both regulations and market-based instruments to dramatically accelerate deployment of high efficiency technologies and electrification to heat pumps, while the grid fully decarbonizes well before mid-century.</td><td rowspan="3">Aggressive (more aggressive codes and standards take effect in 2025)</td><td rowspan="2">Aggresive (mkt. entry of breakthrough tech. in 2030)</td><td rowspan="5">Aggressive (E3 Most Aggressive)</td><td rowspan="5">Switch to HPs</td><td>None</td><td rowspan="5">Aggressive (GridSIM 100x2035)</td></tr>
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Electrification rates are externally determined via Guidehouse scenarios developed for the BTO E3 Inititiative

Scenario	Federal / Utility Incentives	State / Local Restrictions*	Product Innovations	Drivers (Key Differences Highlighted in BOLD)
Conservative Scenario	Modest federal, few utilities	Few for NC, none for Existing	Low GWP refrigerants, grid interactive	• Moderate market transformation expansion by BTO, utility, and industry groups • Few utilities offer substantial incentives for electrification • Modest federal incentive for heat pump conversions (targets customers that already have attractive lifecycle cost savings, such as electric resistance, propane, and fuel oil) • Few state and local governments restrict natural gas for new construction
Optimistic Scenario	Moderate, federal, more utilities	Some for NC, none for Existing	Affordable CCHPs, 110V HPWHs	• **Large market transformation expansion** by BTO, utility, and industry groups • **More utilities offer substantial incentives for electrification** • **Moderate federal incentive** for heat pump conversions (targets customers that already have attractive lifecycle cost savings, such as electric resistance, propane, and fuel oil) • **Some state and local governments** restrict natural gas for new construction
Aggressive Scenario	Large federal, more utilities	More for NC, some for Existing	Affordable CCHPs, 110V HPWHs	• Large market transformation expansion by BTO, utility, and industry groups • More utilities offer substantial incentives for electrification • **Large federal incentive for heat pump conversions (targets customers with more challenging conversions, as well as some environmentally focused gas customers)** • **More state and local governments restrict natural gas for new construction, and some provide significant incentives and/or restrictions for existing homes**
Most Aggressive Scenario	Large federal, most utilities	Most for NC, most for Existing	Affordable CCHPs, 110V HPWHs	• Large market transformation expansion by BTO, utility, and industry groups • **Most utilities offer substantial incentives for electrification** • Large federal incentive for heat pump conversions (targets customers with more challenging conversions, as well as some environmentally focused gas customers) • **Most state and local governments restrict natural gas for new construction, and provide significant incentives and/or restrictions for existing homes**

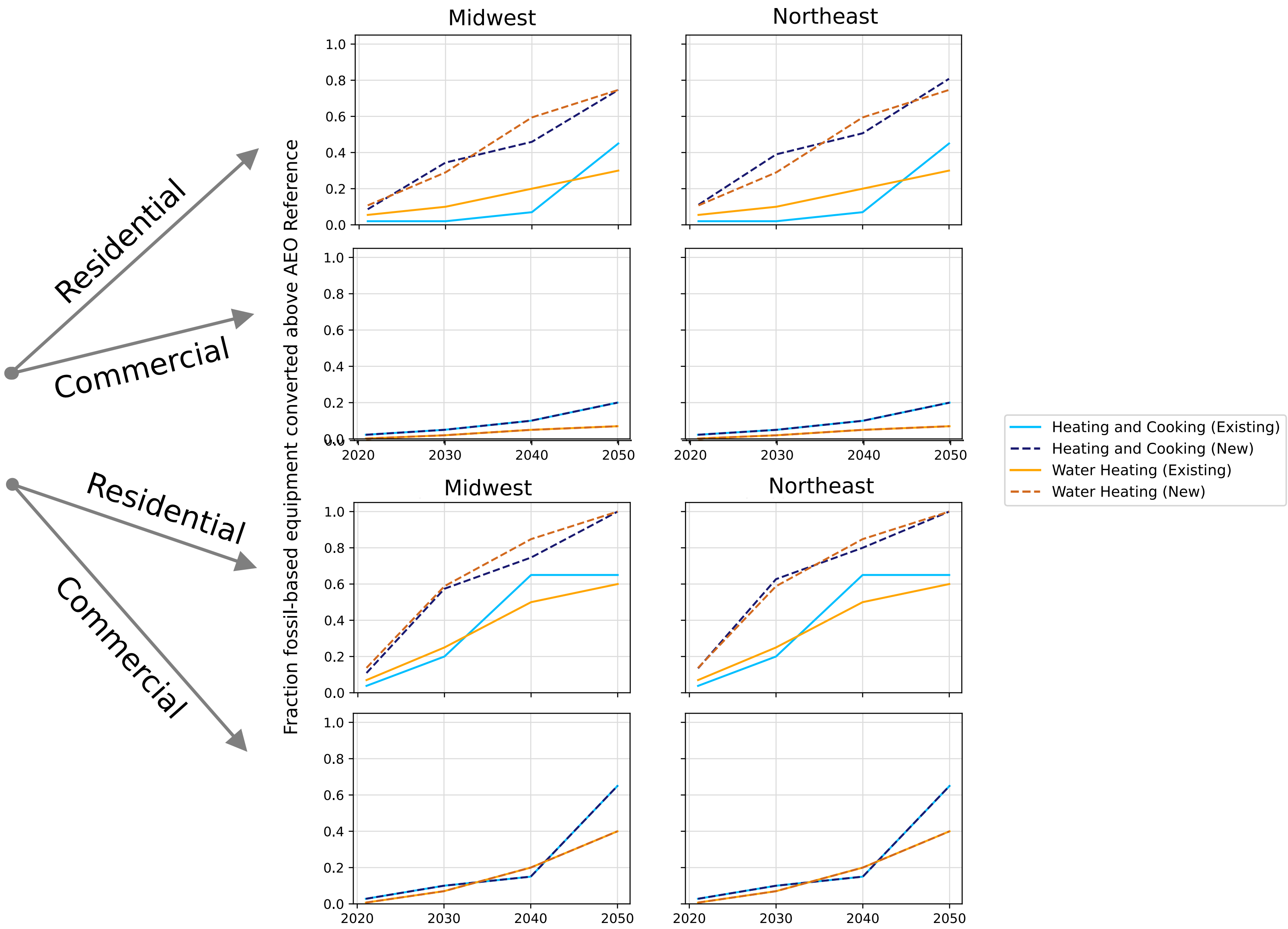
Increasing levels of :

- Federal / utility incentives
- State / local policy support
- Marketing support
- Certification development
- Product innovations

Electrification rates from Guidehouse E3 Initiative scenarios

Overall Heat Pump Sales Shares

	2030 Sales Market Share	2050 Sales Share
Conservative Scenario	27%	44%
Optimistic Scenario	34%	67%
Aggressive Scenario	50%	79%
Most Aggressive Scenario	61%	87%



Heating/WH/cooking stock resulting from E3 scenarios

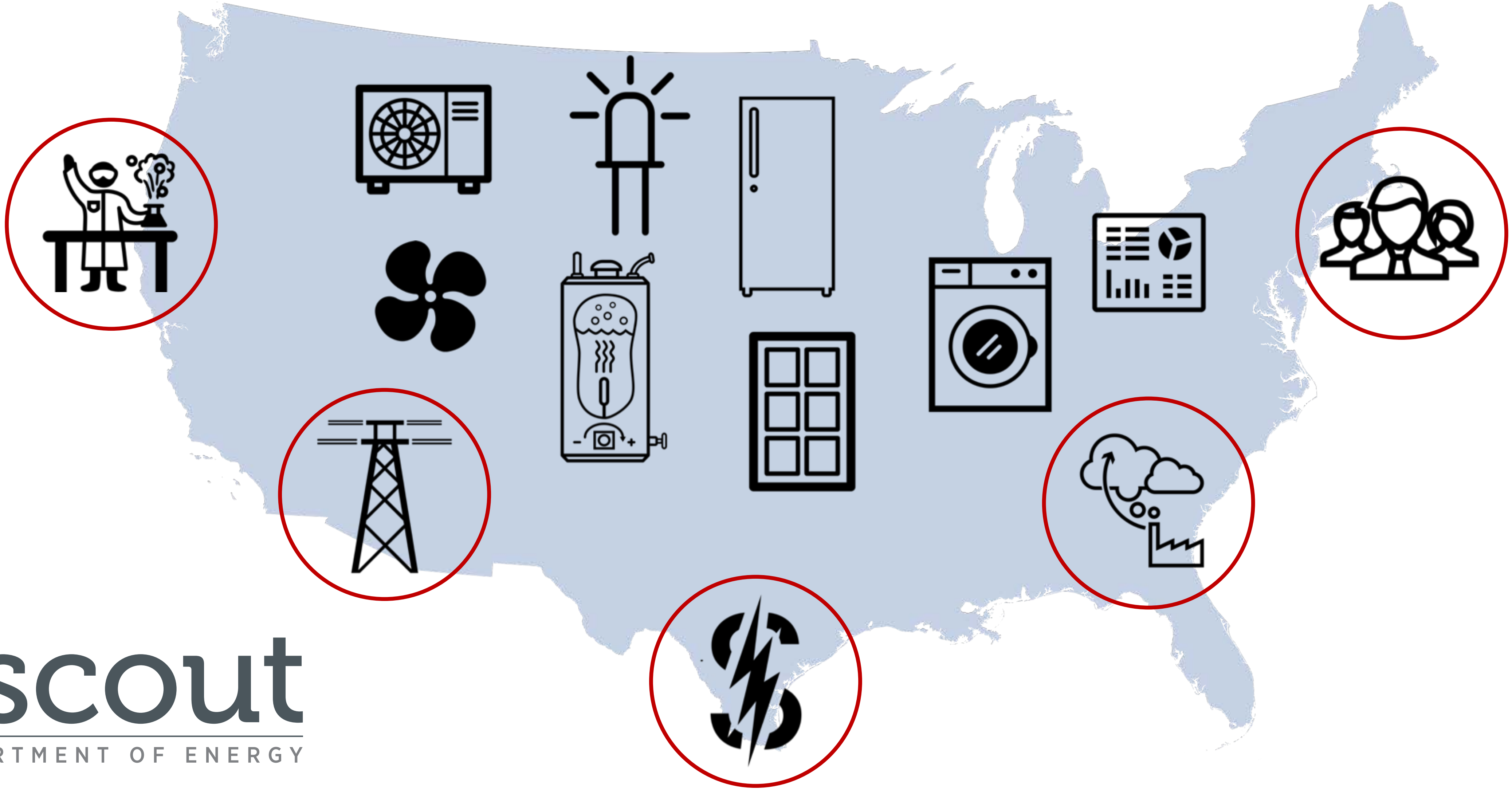
RESIDENTIAL	2030 AEO 2021 Ref. (# units)	2030 Decarb Scn. 1 (# units)	2030 Decarb Scn. 2 (# units)	2030 Decarb Scn. 3 (# units)	2050 AEO 2021 Ref. (# units)	2050 Decarb Scn. 1 (# units)	2050 Decarb Scn. 2 (# units)	2050 Decarb Scn. 3 (# units)
Heating Technology								
Electric ASHP	29,573,784	39,760,129	37,826,312	46,885,405	37,517,054	103,515,369	91,466,921	136,283,377
Electric Resistance	31,545,833	31,545,833	27,177,674	24,420,557	33,974,131	33,974,131	10,866,652	1,206,123
Geothermal HP	2,417,474	2,417,474	2,417,474	2,417,474	4,484,544	4,484,544	4,484,544	4,484,544
Fossil Furnace/Boiler/NGHP	80,663,533	70,477,188	76,779,164	70,477,188	91,725,682	25,727,367	60,883,294	25,727,367
Wood Stoves	3,095,178	3,095,178	3,095,178	3,095,178	2,579,450	2,579,450	2,579,450	2,579,450
Total Heating	147,295,802	147,295,802	147,295,802	147,295,802	170,280,861	170,280,861	170,280,861	170,280,861
Total Heating (% electric)	43%	50%	46%	50%	45%	83%	63%	83%
WH Technology								
Electric HPWH	5,036,041	16,763,979	18,573,175	35,002,933	11,762,581	84,053,329	104,300,703	143,504,495
Electric Resistance	58,550,161	58,550,161	50,693,406	40,311,207	59,611,812	59,611,812	7,809,360	160,646
Solar WH	1,867,592	1,867,592	1,867,592	1,867,592	2,097,923	2,097,923	2,097,923	2,097,923
Fossil Storage	72,462,963	60,735,025	66,782,584	60,735,025	82,105,643	9,814,895	41,369,973	9,814,895
Total WH	137,916,757	137,916,757	137,916,757	137,916,757	155,577,959	155,577,959	155,577,959	155,577,959
Total WH (% electric)	47%	56%	52%	56%	47%	94%	73%	94%
Cooking Technology								
Electric	101,241,519	110,425,756	104,160,030	110,425,756	108,204,741	171,279,229	138,252,857	171,279,229
NG	53,252,371	44,068,134	50,333,860	44,068,134	63,898,890	824,402	33,850,774	824,402
Other	6,974,305	6,974,305	6,974,305	6,974,305	6,368,283	6,368,283	6,368,283	6,368,283
Total Cooking	161,468,195	161,468,195	161,468,195	161,468,195	178,471,914	178,471,914	178,471,914	178,471,914
Total Cooking (% electric)	63%	68%	65%	68%	61%	96%	77%	96%

COMMERCIAL	2030 AEO 2021 Ref. (tBtu served)	2030 Decarb Scn. 1 (tBtu served)	2030 Decarb Scn. 2 (tBtu served)	2030 Decarb Scn. 3 (tBtu served)	2050 AEO 2021 Ref. (tBtu served)	2050 Decarb Scn.1 (tBtu served)	2030 Decarb Scn. 2 (tBtu served)	2050 Decarb Scn. 3 (tBtu served)
Heating Technology								
Electric ASHP	76.1	123.8	108.2	132.7	68.6	461.2	276.0	498.7
Geothermal HP	8.8	8.8	8.8	8.8	4.0	4.0	4.0	4.0
Electric Resistance	64.5	64.5	59.4	55.6	45.8	45.8	22.2	8.3
Other Fossil	1185.0	1137.4	1158.0	1137.4	1110.8	718.2	927.0	718.2
Total Heating	1334.4	1334.4	1334.4	1334.4	1229.3	1229.3	1229.3	1229.3
Total Heating (% electric)	11%	15%	13%	15%	10%	42%	25%	42%
WH Technology								
Electric HPWH	2.4	33.9	13.2	36.3	3.7	309.1	107.8	318.5
Electric Resistance	17.8	17.8	17.1	15.4	13.2	13.2	8.7	3.9
Solar WH	5.8	5.8	5.8	5.8	6.2	6.2	6.2	6.2
Other Fossil	508.8	477.3	498.7	477.3	586.5	281.0	486.8	281.0
Total WH	534.8	534.8	534.8	534.8	609.5	609.5	609.5	609.5
Total WH (% electric)	5%	11%	7%	11%	4%	54%	20%	54%
Cooking Technology								
Electric	55.593	66.5	61.8	66.5	51.141	148.8	98.5	148.8
NG	118.862	107.9	112.6	107.9	149.2	51.5	101.8	51.5
Total Cooking	174.46	174.46	174.46	174.46	200.34	200.34	200.34	200.34
Total Cooking (% electric)	32%	38%	35%	38%	26%	74%	49%	74%

*Note: all data based on AEO 2021 reference case

A2: Additional Scout methodological details and results

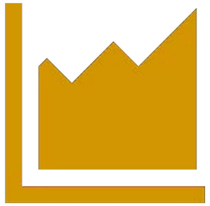
Which building technologies or operational approaches will most impact energy use, CO_2 emissions, and consumer costs?



scout
U.S. DEPARTMENT OF ENERGY

Scout standardizes assessment of specific buildings sector interventions vs. a regularly updated counterfactual forecast

Reference Case Forecast (annual through 2050)



- Energy demand "**segmentation**" (by region, building, fuel, end use, technology)
- Building and technology **stock evolution** (annual # buildings, floorspace, # units)
- Typical **performance per unit** installed stock (annual unit energy consumption)
- Market available **technology mix** (cost, performance, lifetime) and **annual sales**
- **Emissions intensities** (e.g., Mt CO_2/MWh) and **energy costs** (e.g., $/kWh) by fuel

Sector-Specific Interventions (building or "demand-side" measures)

- **Efficiency** (persistent performance improvement); **flexibility** (modify hourly demand); **fuel switching/electrification** (switch from fossil to electric equip.)
- Reduce service demand (e.g., shell improvements) vs. reduce the energy needed to meet given level of service (e.g., a higher performing air conditioner)
- Measure attributes: **Market entry/exit year; applicable baseline segment(s); installed cost** (e.g., $/unit); **energy performance** (e.g., COP); **lifetime** (years); **dynamic load management features** (shift, shed, reshape hourly demand)
- Supply-side interventions (e.g., a cleaner power grid) may also be represented

Scout outputs cover key energy, emissions, and cost impact metrics across multiple geographic and temporal scales

Energy

- **Consumption** (annual MMBtu, Quads, or TWh, regional or national)
  - Site (or "Final") vs. source (or "Primary")
- Electricity: **Demand** (hourly MW or GW, regional or national)
  - Rate of electricity consumption, averaged across time period

Emissions

- **CO_2** emissions (annual Mt CO_2 , regional or national)
  - Direct (on-site combustion) vs. indirect (upstream electricity generation)
  - Coming soon: **CO_2e** maps other GHGs (e.g., from methane, refrigerants) to the warming potential (GWP) of CO_2

Costs

- **Technology** retail or installation costs ($/unit, $/service capacity, or $/ft^2 floor area)
- **Consumer** energy costs (annual $, regional or national)
- Electricity: Pair with grid models to assess **power system costs** ($/MWh hourly generation, marginal or total, regional or national)

Analysis flow: from measure definition to impact estimation

INPUTS

Baseline definition

Annual energy/ emissions/costs (2020-2050)*; hourly energy demand**

Energy Conservation Measure (ECM) definition

Defined for Building Type(s), Climate Zone(s), End Use(s), Fuel Type(s) and Tech Type(s)

Building Stock

Bldgs., Floor Area

Technology Stock

Units, Energy Use

Cost, Performance, and Lifetime

Adoption Parameters

Cost
Performance
Lifetime
Market Entry Year

Dynamic Load Management Features

ENGINE

For each year, determine adoption of all available ECMs (those that have entered the market) subject to stock and flow dynamics and ECM competition

Stock and Flow Dynamics

New stock and stock up for replacement or retrofit (baseline and ECM)

ECM Competition

Determine which technologies will be adopted by different types of consumers based on technology CAPEX and OPEX

OUTPUTS

ECM/Portfolio Impacts

Energy savings

Avoided CO_2 emissions

Avoided energy costs

Hourly load impacts (peak, off-peak, 8760)

ECM/Portfolio Cost Effectiveness

IRR
Simple Payback
Cost of Conserved Energy/Carbon

* Based on EIA Annual Energy Outlook Reference Case; ** Based on hourly end use load shapes from ResStock, DOE Commercial Prototype Buildings

Adoption assumptions are staged across calculation steps

CALCULATION STEP | **HIGH-LEVEL EQUATIONS** | **ANNUAL SAVINGS OUTCOME**

Set baseline, estimate technical impact potential

$$\Delta M_y = \sum_{c=1}^{C} \sum_{b=1}^{B} \sum_{f=1}^{F_b} \sum_{u=1}^{U_{b,f}} \sum_{t=1}^{T_{b,f,u}} \sum_{v=1}^{V} (M_{base})_{X,y} - (M_{ecm})_{X,y}$$

Where ΔM= Tech. potential ECM impact on metric M (energy, CO_2, cost); M_{base}=Total AEO baseline value for metric M ;
M_{ecm} = total value for metric M after application of ECM;
c, b, f, u, t, v, y=AEO climate zone, building type, fuel type, end use, tech. type, bldg. vintage, and year, respectively; X=c, b, f, u, t, v

Add stock and flow dynamics

$$(\Delta M_{sf})_{X,y} = (\Delta M)_{X,y} * (\lambda_n + \lambda_r + \lambda_{re})_{X,y}$$

Where $(\Delta M_{sf})_{X,y}$= Potential ECM impact on metric M (energy, CO_2, cost) in baseline segment X and year y after technology stock and flow adjustment; λ_n, λ_r, λ_{re} = tech. stock addition rate (from AEO), stock replacement rate (1/base life) and retrofit rate (0.01) for AEO baseline segment X

Add ECM competition

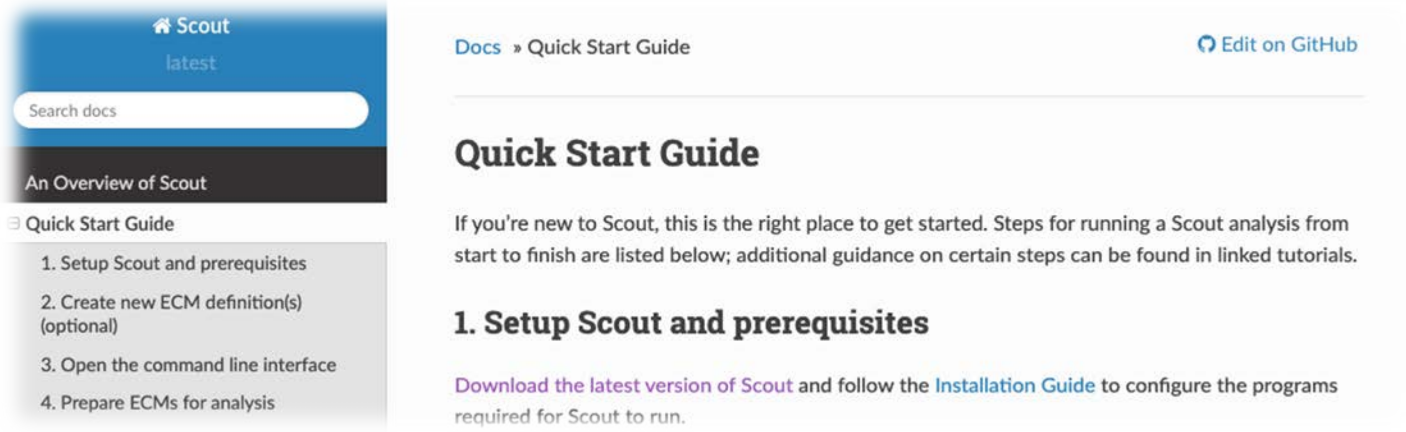
$$(\Delta M_{sf,c})_{X,y} = (\Delta M_{sf})_{X,y} * a_{X,y,C},$$
$$a_{X,y,C} = f((c_{cap})_y, (c_{op})_y, b)$$

Where $(\Delta M_{sf,c})_{X,y}$= Potential impact on metric M (energy, CO_2, cost) in baseline segment X and year y after technology stock/flow AND competition adjustment; $a_{X,C}$= competition adj. fraction for baseline segment X, year y, and competing ECM set C

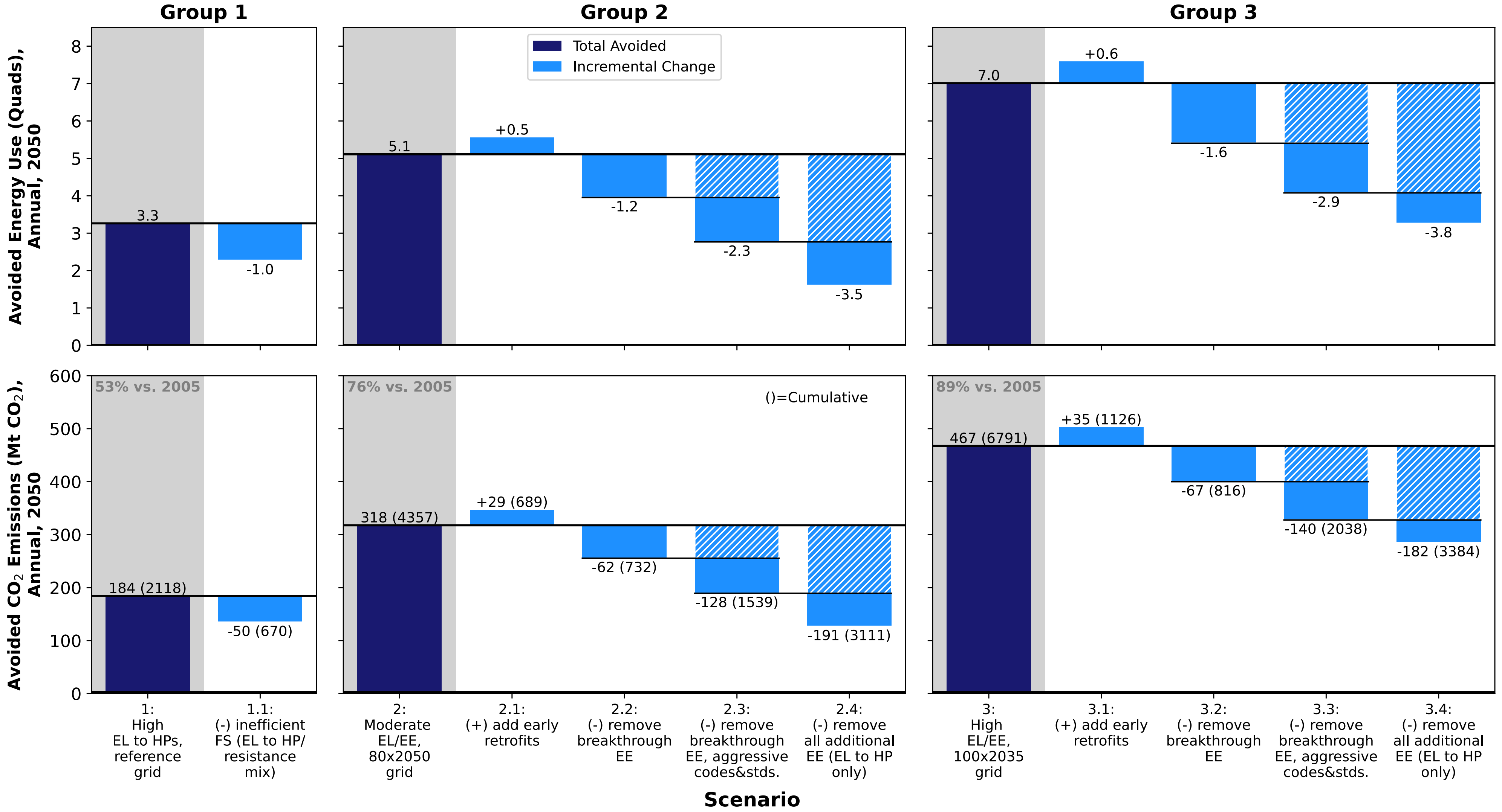
Access Scout's web-based user interface and extensive documentation to help you get started

Visit scout.energy.gov to explore baseline energy and emissions markets for your innovations; define, edit, and visualize measure results; and access further documentation with guidance on how to run custom, end-to-end Scout analyses.

Scout Core Measure Scenarios and source code are also available.

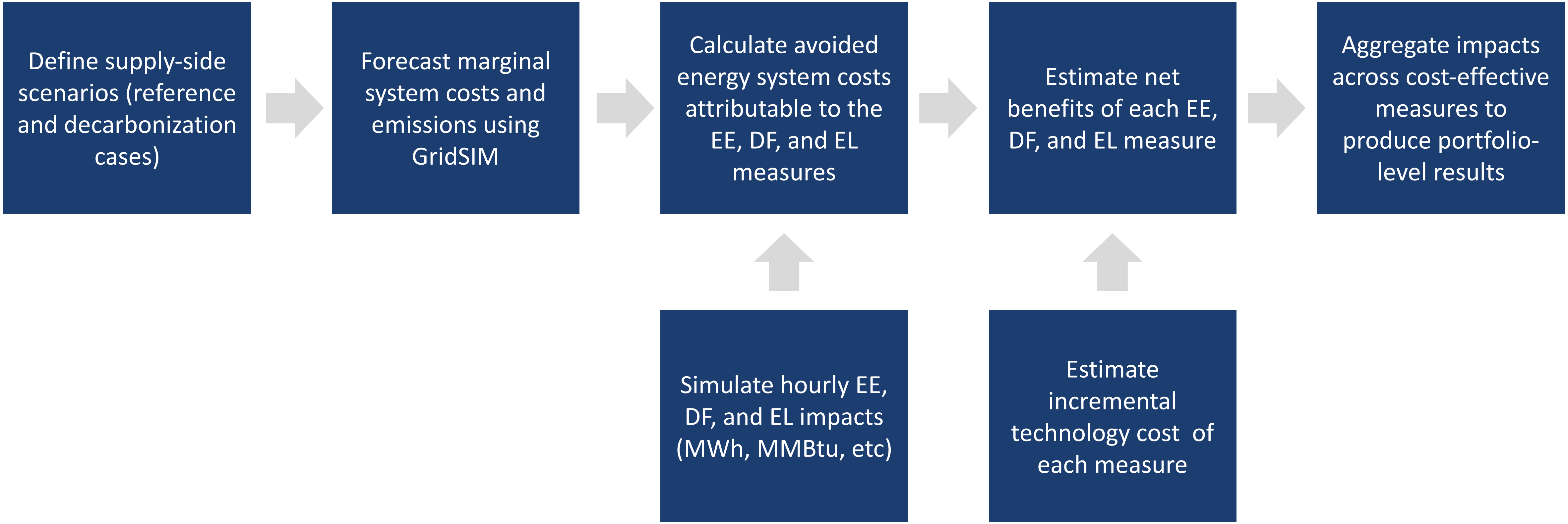


2050 energy and CO_2 reductions: The absence of aggressive efficiency deployment substantially limits reductions



A3: Additional GridSIM methodological details

Methodology overview



GridSIM modeling framework

INPUTS

Supply
- Existing resources
- Planned builds and retirements
- Fuel prices
- Investment/fixed costs
- Variable costs

Demand
- Representative day hourly demand
- Forecasts of annual and peak demand
- Planning reserve margins

Transmission
- Zonal limits
- Intertie limits

Regulations and Policies
- State energy policies and procurement mandates

GridSIM OPTIMIZATION ENGINE

Objective Function
- Minimize NPV of Investment & Operational Costs

Constraints
- Planning Reserve Margin
- Hourly Energy Balance
- Regulatory & Policy Constraints
- Resource Operational Constraints
- Transmission Constraints

OUTPUTS

Marginal CO_2 Emissions Rate

Marginal Cost of Capacity

Marginal Cost of Energy

Additional Marginal Cost of Satisfying Carbon Cap

The three modeling cases

Will be updated to include building electrification load

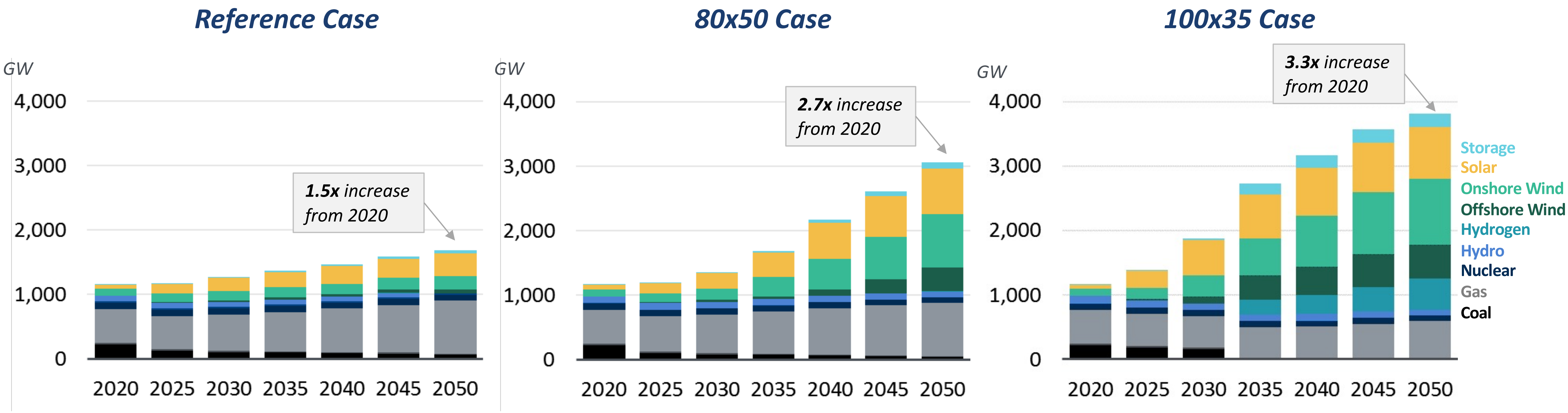
	Reference Case	80x50 Case	100x35 Case
Renewable Generation and Emissions Targets	**Current RPS state mandates**	**80% reduction in emissions by 2050, relative to 2005 level** *53% reduction in emissions by 2030 (state-level requirements are more stringent than national requirement through 2030)*	**Zero emissions by 2035** *79% reduction in emissions by 2030, relative to 2005 level;* *100% reduction in emissions by 2035 and all subsequent years*
Electricity Demand Growth	**Minimal vehicle electrification by 2050** *8% of light-duty vehicles are BEV/PHEVs**	**High electrification of vehicles by 2050** *95% light-duty vehicles are BEV/PHEVs, 50% medium-duty are BEVs, 35% heavy-duty are BEVs*	**Same assumptions as 80x50 case**

Sources and Notes:
See appendix for additional modeling detail. Reference Case's renewable target and demand growth assumptions are consistent with AEO 2020 reference case and NREL Standard Scenario Mid Case.
*24.5 million BEV/PHEVs estimated to be on the road in 2050. Projection estimated using the following data: new light-duty vehicle sales from the AEO 2020 reference case, Light-Duty Alternate Fuel Vehicle Registrations and U.S. Plug-in Electric Vehicle Sales by Model from the US Department of Energy. In total, 308 million LDVs are assumed on the road in 2050 based on reviewed studies' projections.

Power generation capacity

Decarbonizing U.S. power supply will require a massive buildout of renewable generation, energy storage, and flexible clean generation technologies.

Total Installed Generation Capacity, by Case



Notes: Some fossil fuel generation remains online after the power sector has been decarbonized. This generation exists exclusively for reliability purposes, would be utilized infrequently, and could run on renewable gas in the rare instances when it is needed. In addition to the resource types listed in the figure legend, the capacity mix includes pumped hydro, biogen, and geothermal generation, though they are not readily visible to due to their small contribution relative to total installed capacity.

Analyzing the net system benefits of EE, DF and FS

We compare the system benefits of each measure to its incremental technology cost

Benefit or Cost Category	Description
Reduced electricity generation variable costs	Reduced cost of generating electricity (i.e., fuel and variable O&M). Forecasted with hourly granularity using GridSIM.
Reduced electricity generation fixed costs	Reduced investment in generation capacity and fixed O&M. Driven by load growth and clean energy requirements, as forecasted using GridSIM.
Reduced T&D costs	Deferred investment in T&D system due to load reductions. Currently assume $25/kW-year based on review of utility studies.
Reduced direct-use fuel costs	Reduced cost of directly burning fuels (primarily natural gas) to heat buildings.
Incremental technology cost	Incremental cost of each EE, DF, and EL measure relative to a baseline measure.

Note: Benefits can be negative for some measures. For example, cooking electrification measures have negative electricity benefits in the sense that they increase electricity-related costs. Those negative benefits are at least partially offset by reductions in the use of other fuels.

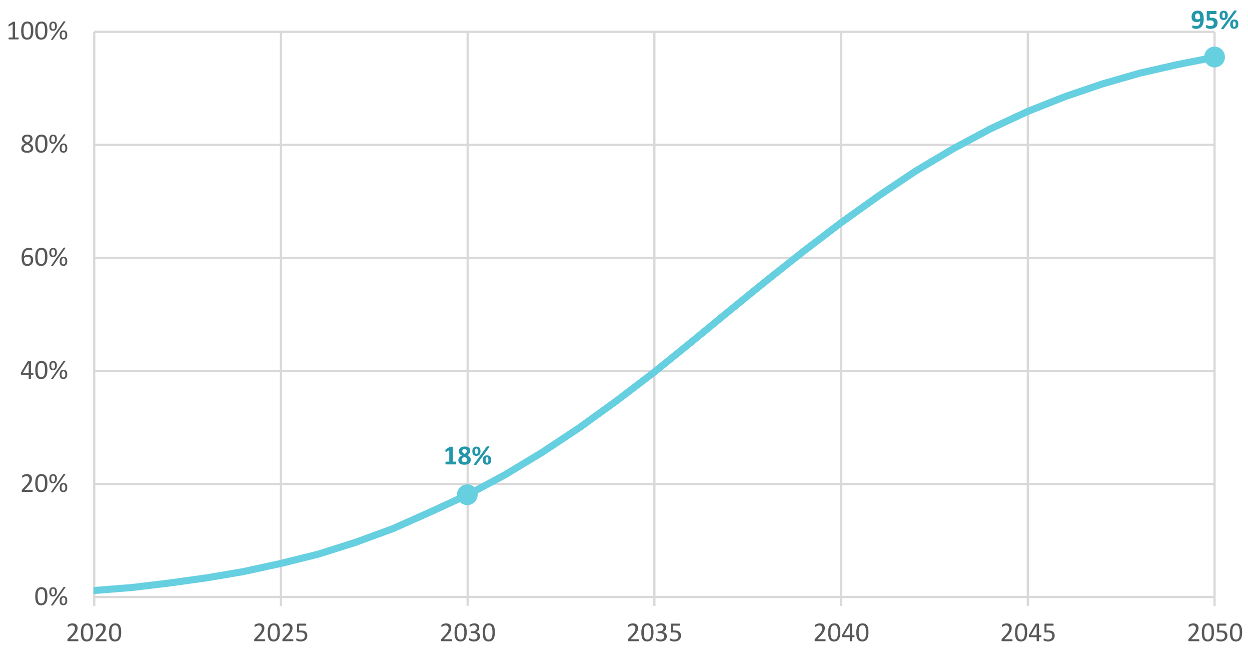
Our Reference Case assumptions are primarily based on the AEO Reference Case, with some differences

Data Element	Source
Zones	**AEO 2021**: EMM Regions
Transmission topology and limits	**AEO 2020 Ref. Case**: Interregional Transfer Capability
Existing generator data	**AEO 2021** (capacity, heat rate, location, FOM, VOM)
Fuel prices	**Forward pricing and AEO 2021 Ref. Case** for natural gas; **AEO 2021 Ref. Case**, Tables 3 and 54 for nuclear, coal, oil
New generator costs	**NREL Annual Technology Baseline 2021:** Moderate cost case (Capital, FOM, VOM)
Hourly renewable generation shapes	**NREL Renewable Energy Potential Model** scaled to historical capacity factors
Hourly load shapes	**FERC 714 filing** via S&P Global Market Intelligence (2020 hourly load data)
Load growth	**AEO 2021 Ref. Case**: Annual energy and peak demand forecast (direct from EIA)
Existing plant retirement age	**NREL ReEDS Model Documentation: Version 2019** Tables 10 and 11
Zonal capacity requirements	**AEO 2020**: Planning reserve margins; each EMM must satisfy its own reserve margin
International imports and exports	**EIA Open Data:** U.S. Electric System Operating Data: BA-to-BA interchange (historical hourly interchanges)

Trajectories for EV Adoption in the 80x50 and 100x35 Cases

EV sales are assumed to **follow an s-curve** which—along with expected EV lifetime—determines the # of EVs on the road each year. We fit the S-curve to EV adoption projections for 2050.

Percent of Light-Duty Vehicles on the Road that are Electrified

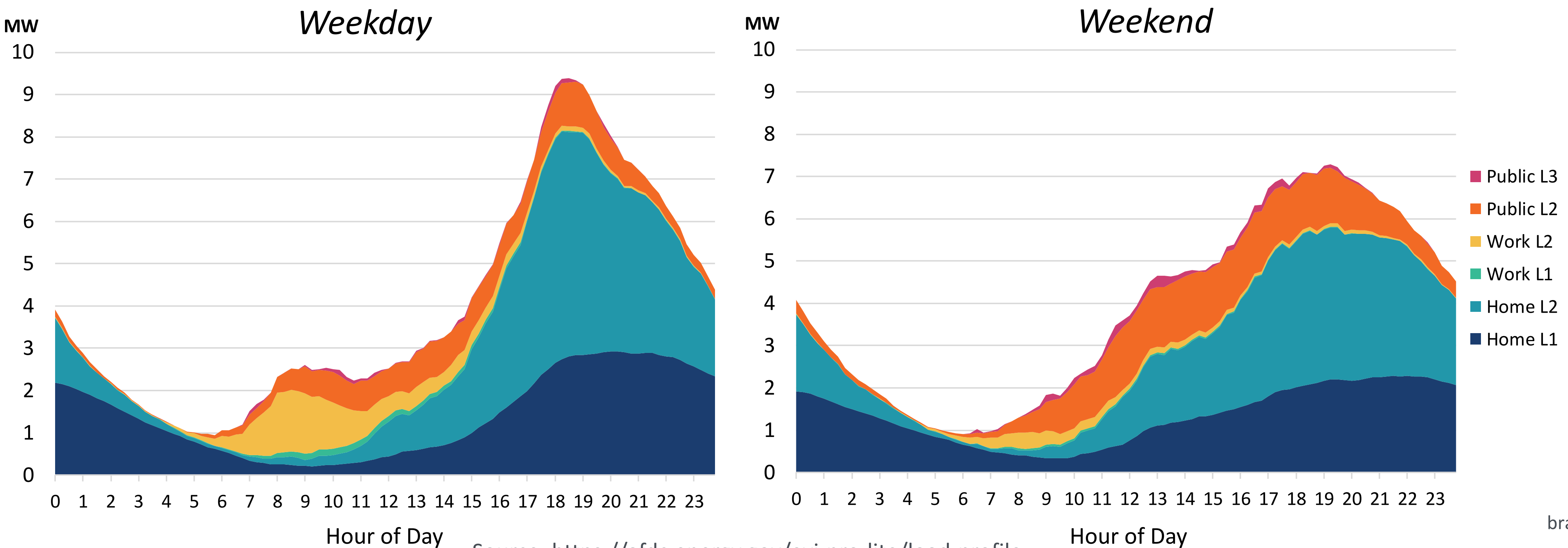


EV Charging Impacts on Power System Load

EV load profiles are from EVI-Pro Lite database and reflect **composite of different charging options**: Level 1-Level 3 at different times of day and locations (home, work, and public)

Assumptions are being developed for the share of BEVs vs. PHEVs, and the share of vehicles participating in **managed charging** to limit impacts on system peak load. (The charts below represent unmanaged charging since managed charging assumptions are still under development.)

Load from Unmanaged Charging: 10,000 EVs, Bay Area California



Source: https://afdc.energy.gov/evi-pro-lite/load-profile

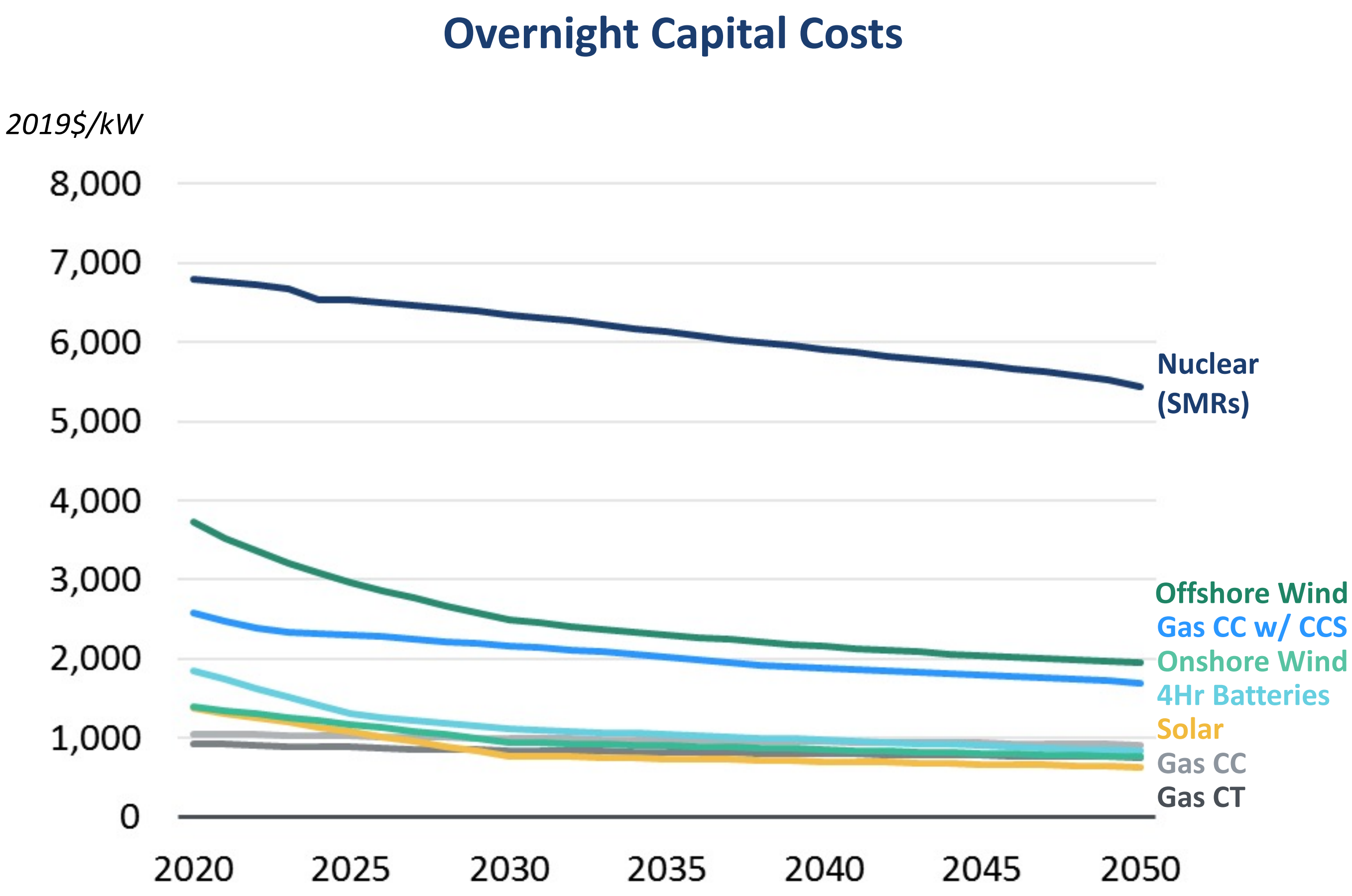
We model the option to add a variety of new power generation resources, including several clean resource types

New resources that can be built by the model:

- Utility-scale solar
- Land-based wind
- Offshore wind
- 4 hour batteries
- Gas CC
- Gas CT
- Nuclear – small modular reactors (SMRs)
- Carbon capture/seq.
- CC fueled by green hydrogen or methane

New resource overnight capital cost assumptions from NREL Annual Technology Baseline (2021)

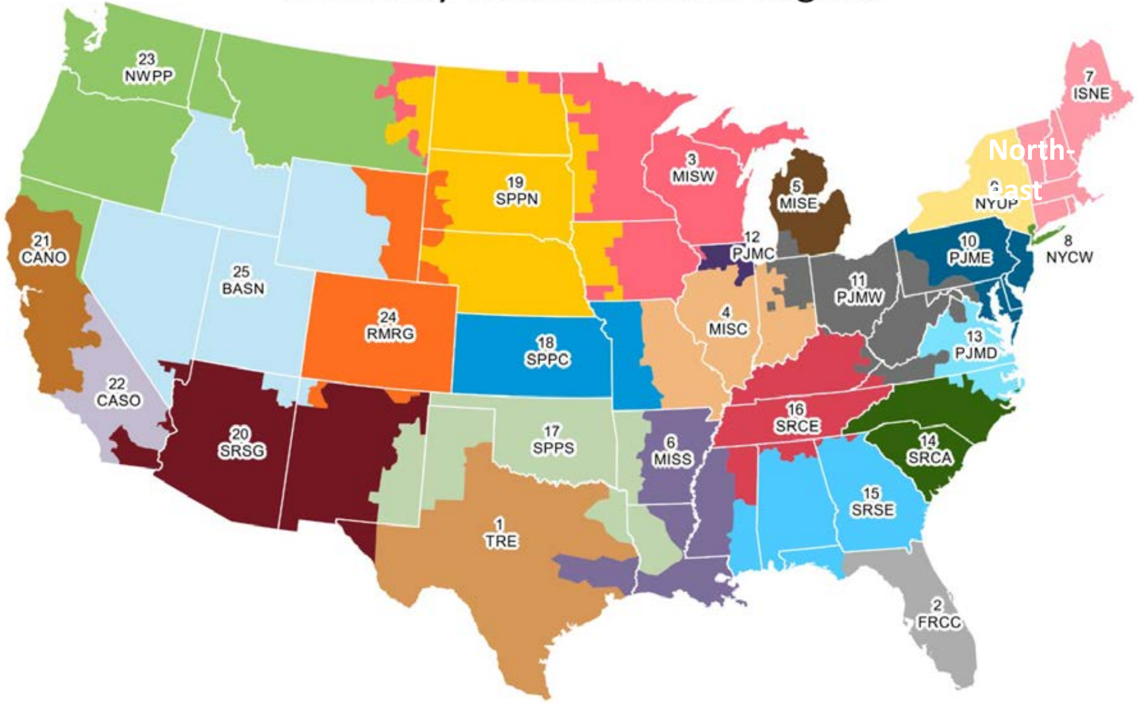
- Provides outlook for new resource costs through 2050
- Use **moderate cost case** trajectories
- All resource costs vary by zone consistent with EIA AEO 2016



Modeled Zones and Transmission

- We model 25 zones, based directly on the EIA's EMM region definitions
- All loads and generators assigned to a zone
- We use a 'pipe and bubble' transmission model to model transmission between regions
  - Each transmission line represented as a maximum MW flow limit between zones
  - Flow limits from AEO 2020
- Energy price separation occurs between zones when transmission lines are fully loaded

Electricity Market Module Regions

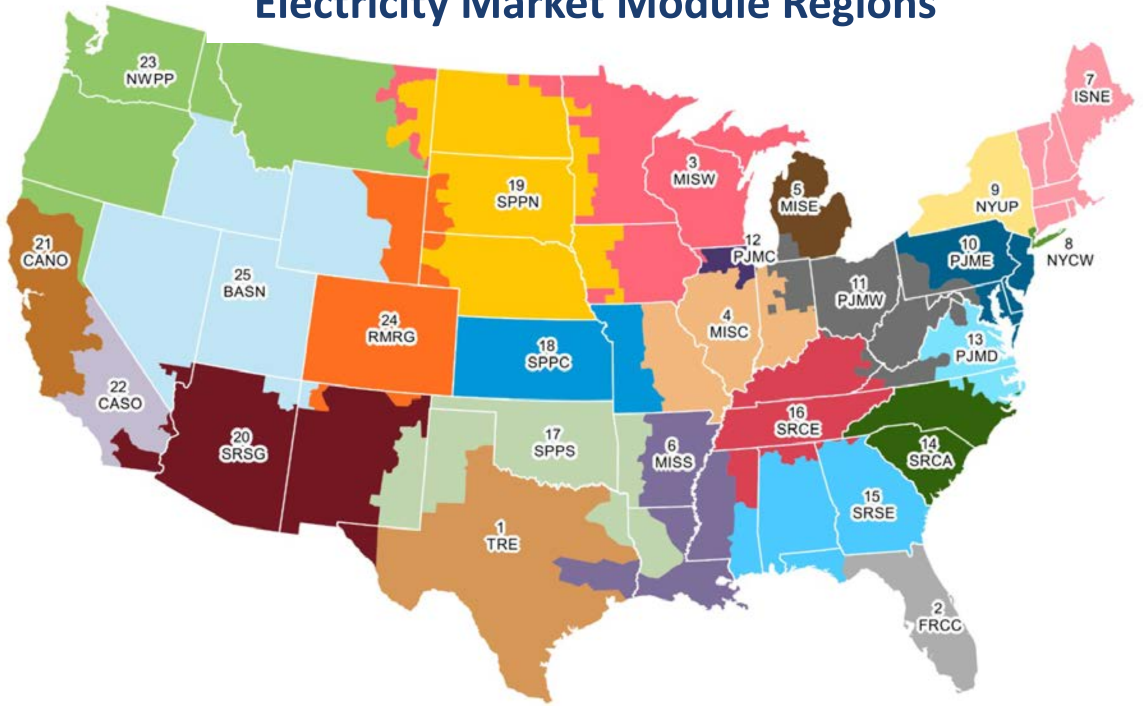


Source: https://www.eia.gov/outlooks/aeo/pdf/nerc_map.pdf

The 25 zones are aggregated into 11 proposed regions to simplify reporting of the results

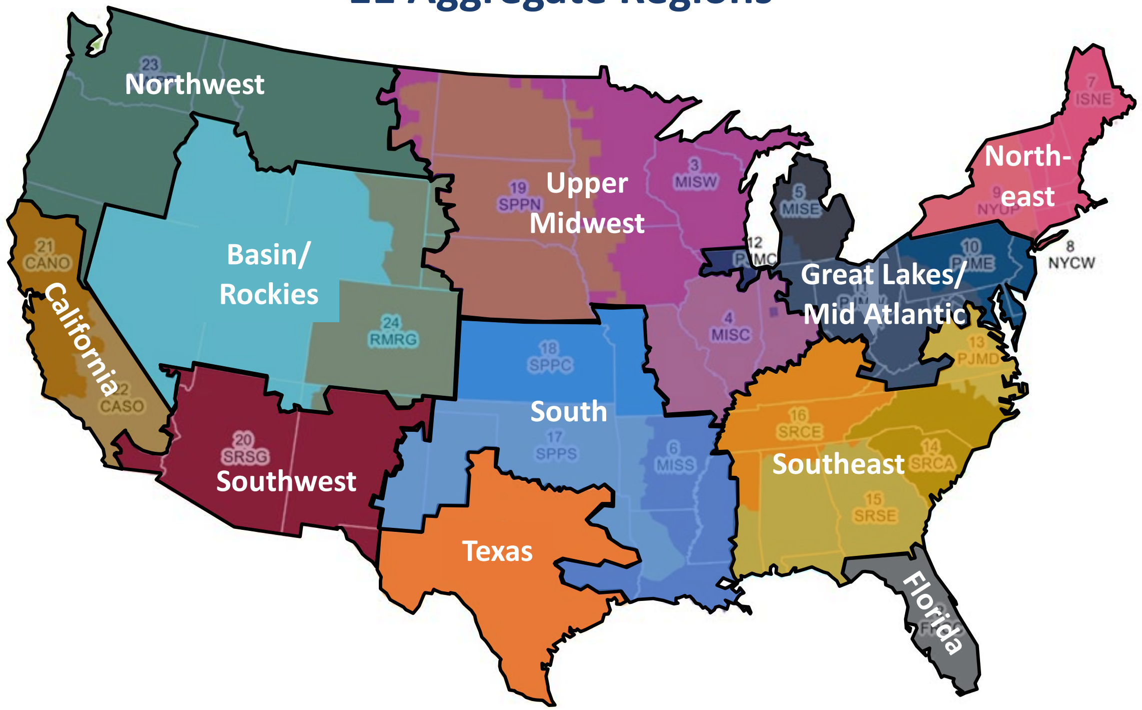
All supply side and Load Flex modeling will be done at the EMM level, but results will be presented at the level of 11 aggregate regions to simplify reporting.

Electricity Market Module Regions



Source: https://www.eia.gov/outlooks/aeo/pdf/nerc_map.pdf

11 Aggregate Regions



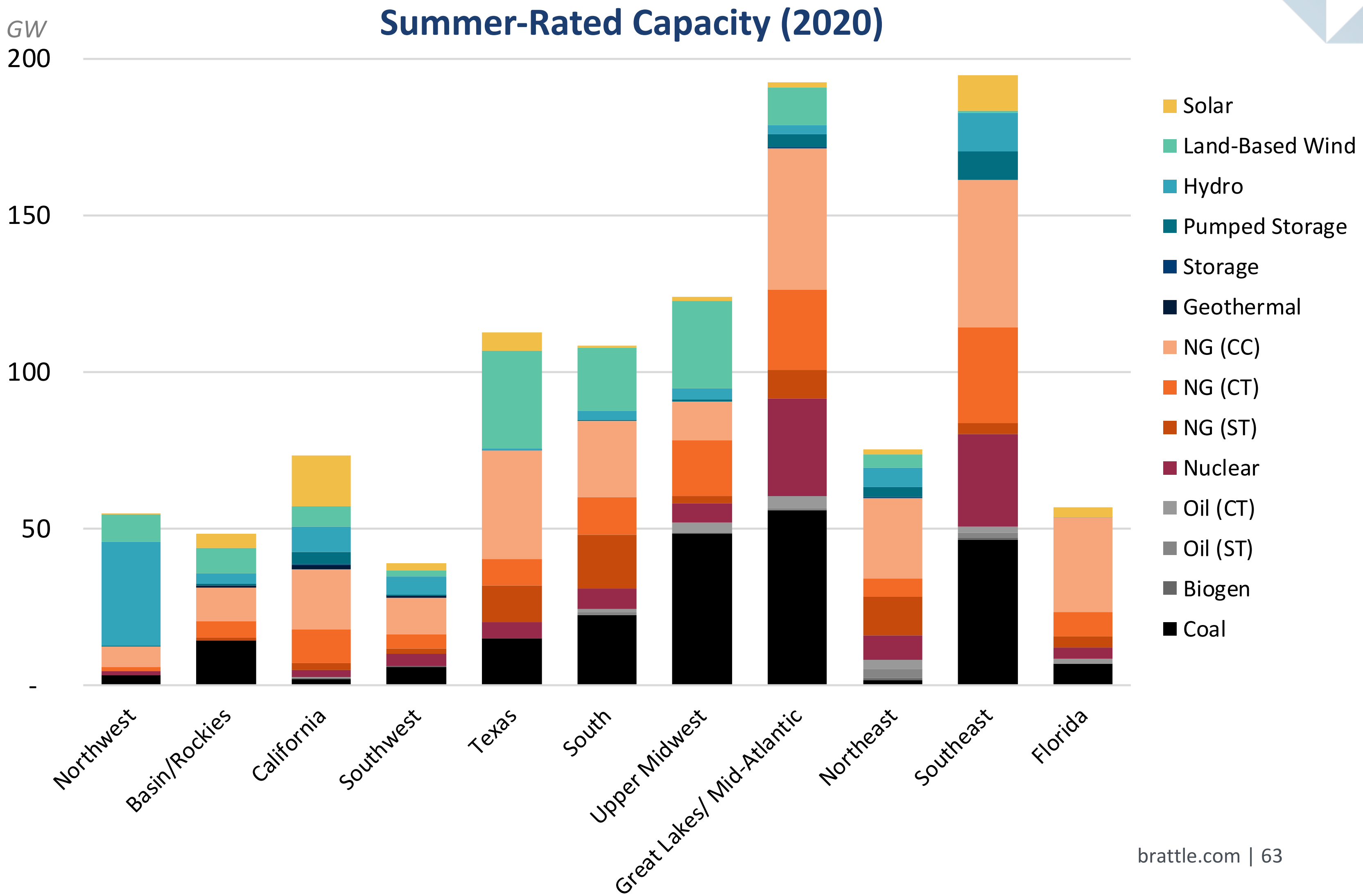
Regions are very similar to the EPA Avert Regions used in the GEB Technical Potential and Roadmap studies, with more granularity in the Northwest

Existing Generators

We model all existing generators using data from AEO 2020.

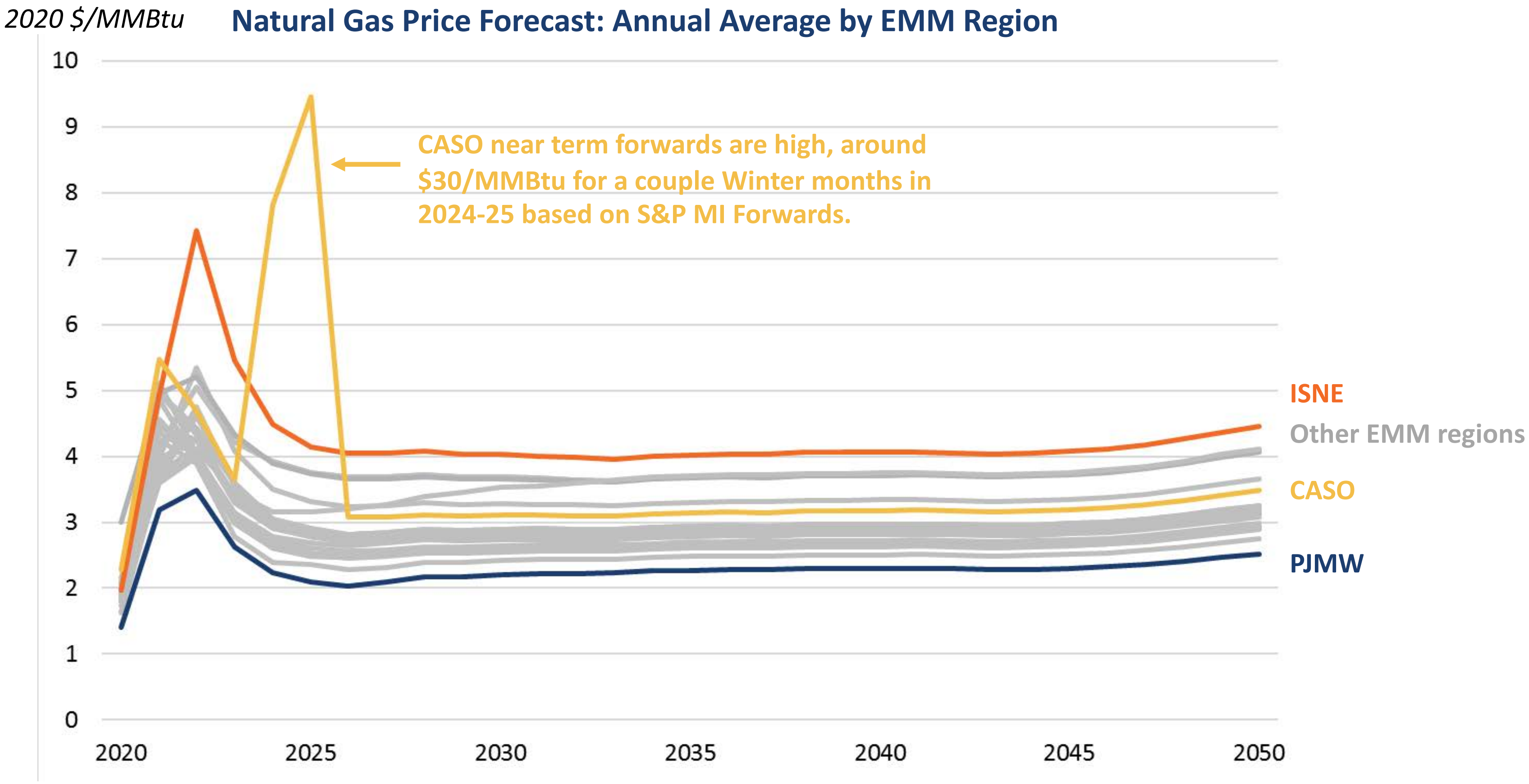
- Generators of like types aggregated by zone and type (e.g., coal, gas CC, nuclear, wind, solar)
- Generator characteristics (e.g., heat rate, VOM, FOM) developed consistent with AEO 2021 data

We model plant retirements using EIA data on average lifetime of generator types (e.g., 46 years for coal generators).



Natural Gas Fuel Prices

Natural gas price projections use forwards for 5 years, then transition to EIA AEO 2021 year-over-year growth rates.



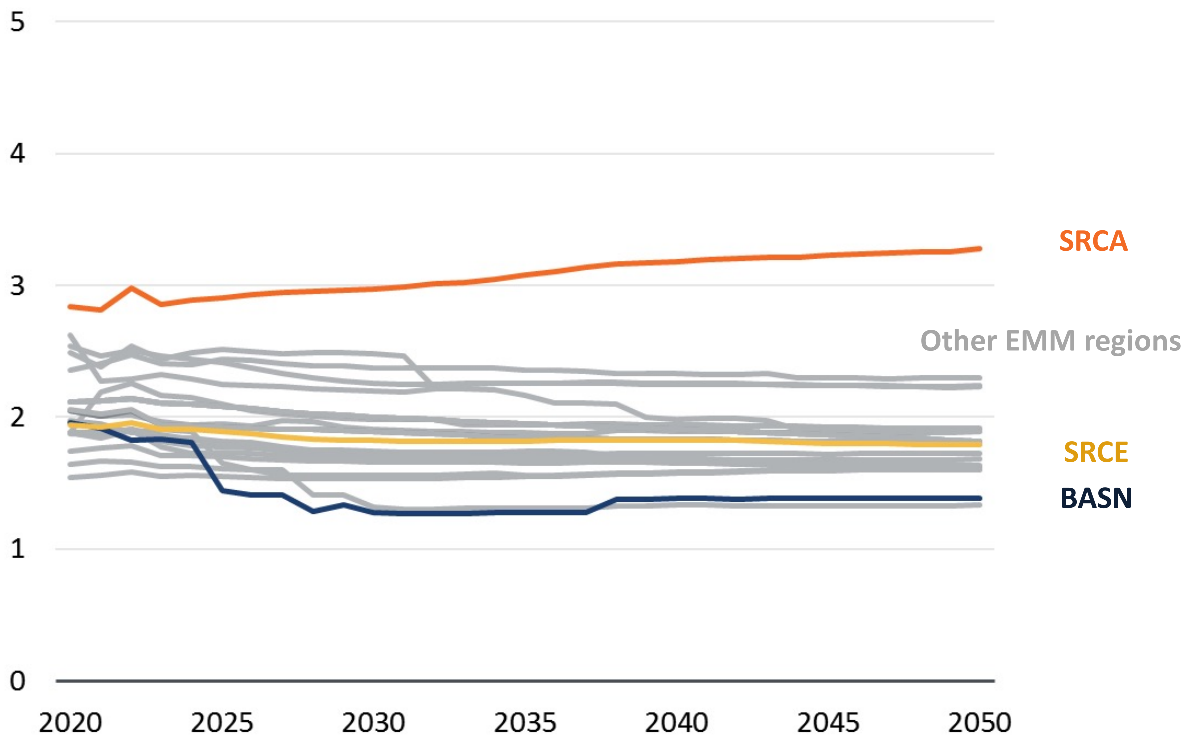
Note: Natural gas price forecast includes all 25 EMM regions. Gas price spot forwards pulled on 11/8/2022.

Coal and Oil Fuel Prices

Coal and oil forecasts are from EIA AEO 2021.

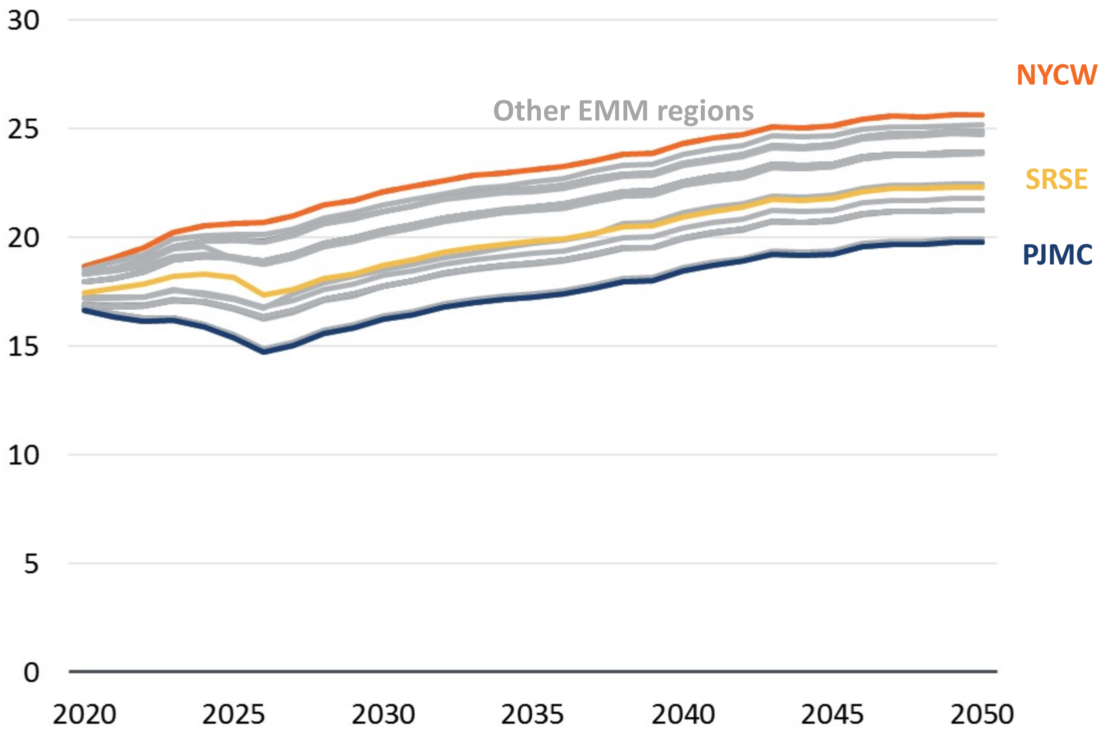
2020 $/MMBtu

Coal Price Forecasts by EMM Region



2020 $/MMBtu

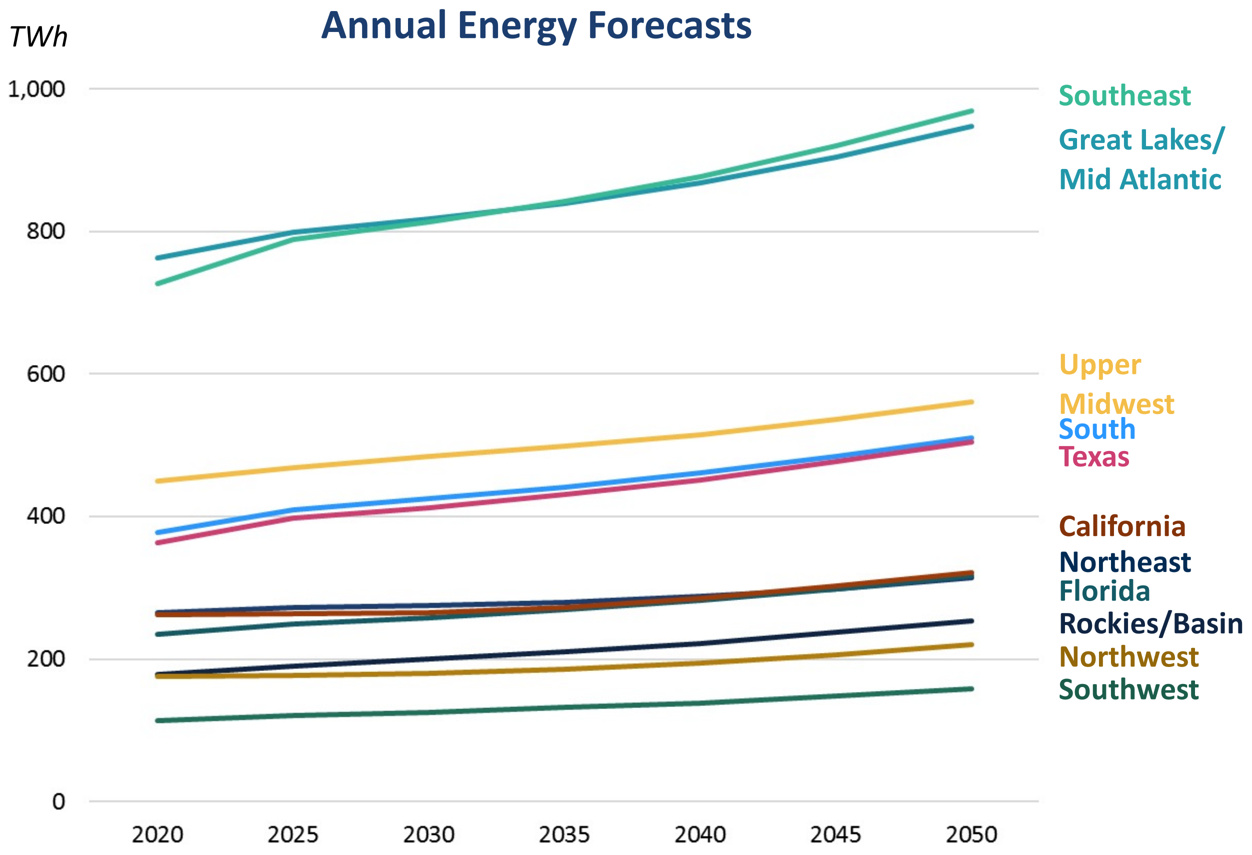
Oil Price Forecasts by EMM Region

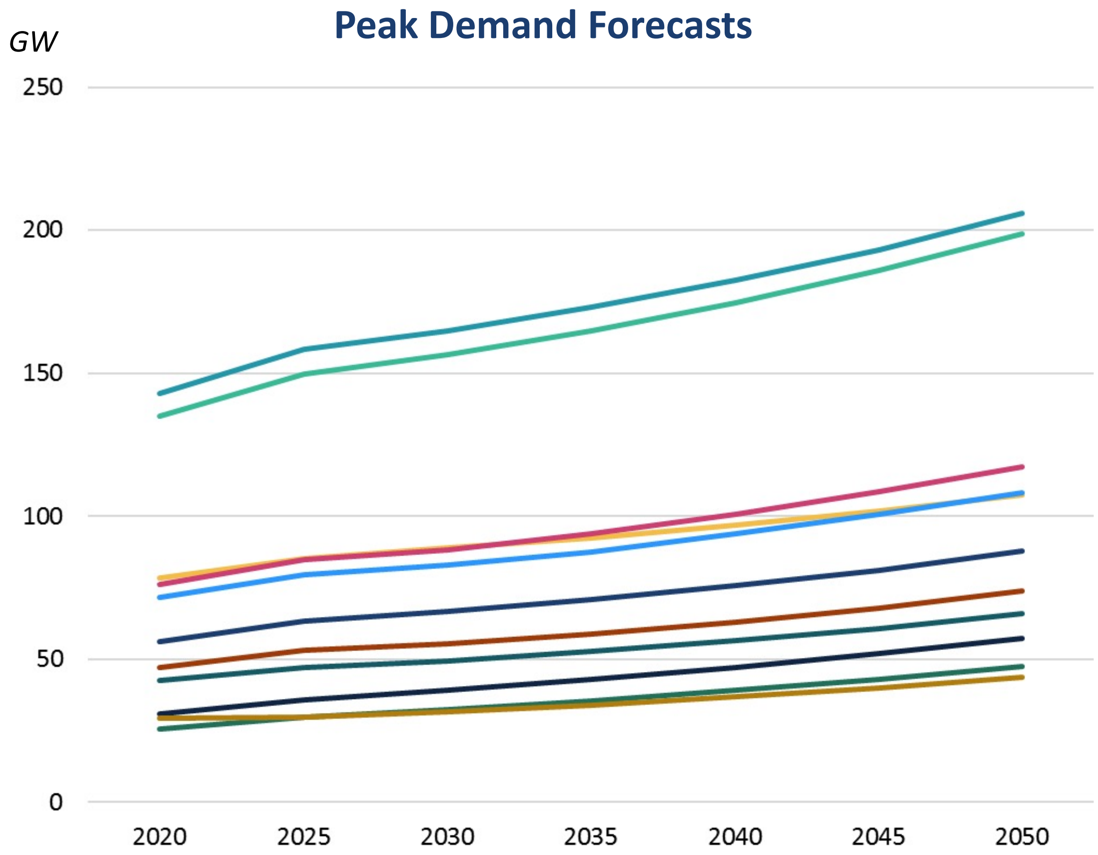


Note: Coal price forecast does not include NYUP, NYCW, and ISNE EMM regions. Oil price forecast includes all 25 EMM regions.

Load growth

Consistent with EIA AEO Reference Case projections, we model growing load and peak demand. We model hourly load in each year consistent with 2020 hourly load shapes.





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